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Can Wildland Fire Use Restore Natural Fire Regimes in Wilderness and Other Unroaded Lands?

Final Report to the Joint Fire Science Program

Project #01-1-1-05

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Executive Summary

Can Wildland Fire Use Restore Natural Fire Regimes in Wilderness and Other Unroaded Lands?

Overview

The goal of this project was to help evaluate the feasibility and effectiveness of wildland fire use (WFU) as a strategy for restoring historical fire regimes in wilderness and on other unroaded lands. Five wilderness areas and national parks were used as study areas to develop our analysis approach, which we then used to evaluate the existing fire management plans at each of these study areas. The information produced resulted in "improved understanding of the options for restoring and managing fire in unroaded, wilderness, and similar areas" and provided a "tool for evaluating and understanding management and restoration goals in unroaded, wilderness, and other areas with restricted access" (Task 1 of RFP 2001-1).

Two rounds of site visits to each study area allowed fire management staff to provide input and feedback on the approach and analysis results in the form of expert knowledge. At the request of fire and resource management staff, additional analyses were conducted to improve their assessments of the risks and opportunities from WFU.

Estimates of the probability of burning were used to evaluate the impact of suppressing ignitions that occur outside designated WFU zones and otherwise would have immigrated into these zones for each study area. Areas were then identified where restoration objectives can be most easily met through the use of natural ignitions. Areas were also identified within WFU zones where meeting restoration objectives through the use of natural ignitions alone may be a challenge due to the suppression activities on adjacent lands.

Results

We developed and used a GIS model, BurnPro, to estimate the average annual probability of burning and to help assess the feasibility of WFU as a strategy for restoring historical fire regimes in wilderness and on other unroaded lands. We used this modeling approach to evaluate the existing fire management plans at each of 5 study areas. Our analyses generated new information that will be helpful for long-term fire and fuels management planning. Each landscape has unique spatial configurations of fuel, ignitions, and topography, and the approach used by BurnPro accounts for the spatial topology and context of each study area. Furthermore, we were able to address cross-boundary influences of fire management. We found that our approach to modeling the probability of burning with BurnPro is suitable for a range of climate regimes.

The project supported planning and management at a number of sites: Gila/Aldo Leopold Wilderness Area (Gila National Forest), Great Smoky Mountains National Park, Selway-Bitterroot Wilderness Area (includes Nez Perce, Clearwater, Lolo and Bitterroot National Forests), Sequoia-Kings Canyon National Parks, and Yosemite National Park. We evaluated WFU strategies as outlined in fire management plans and identified areas where restoration objectives can be most easily met through the use of natural ignitions. We also identified areas within WFU zones where meeting restoration objectives through the use of natural ignitions alone may be a challenge due to the suppression activities on adjacent lands. In addition, we provided information on risks and opportunities of WFU to improve risk assessments.

Our modeling approach was documented in a conference proceedings paper and we are currently working on peer-reviewed journal article. We presented the BurnPro model and resulting analyses at 5 scientific conferences, including one invited presentation. The exposure at national conferences generated considerable interest in BurnPro from the fire management community. For example, as a result of response to our poster presentation at the 2nd

International Wildland Fire Ecology and Fire Management Congress in Orlando, FL, November 2003, we experimentally released a development version of BurnPro for use on the Cloud Peak Wilderness in northeastern Wyoming. More recently, we were asked to develop lecture materials for a unit in Module VI of Technical Fire Management (administered by Washington Institute and Colorado State University). Over the next few months, we plan to present results to management staff at other workshops and training sessions, including the Rocky Mountain Area Fuels and Fire Use workshop and the Northern Rockies Training Center's Managing Wildland Fire for Resource Benefit course. The model is also being evaluated for use in planning hazardous fuels reductions on the Colorado Front Range.

The interest of the research community has also been piqued and we have several opportunities for improving, testing and applying BurnPro. Further development and testing on BurnPro is needed and would be facilitated if any of the following opportunities are funded. We are working with collaborators from the University of Georgia to submit a proposal to NASA in January 2005 that includes further application of BurnPro as a decision support planning tool for Great Smoky Mountains National Park. The USDA Forest Service Rocky Mountain Research Station's Boise Aquatics Lab has a pending JFSP proposal to develop a decision support tool that will likely utilize BurnPro. The Canadian Forest Service has also expressed interest in comparing BurnPro to their regional probability of burning model, BurnP3. Finally, we see promise in using BurnPro to help parameterize fire regimes in landscape vegetation simulation models.

Deliverables

The specific deliverables outlined here exceed our initial proposed list. Electronic and hardcopy versions of all reports and articles will be submitted to the Joint Fire Science Program office.

- Final reports to each study area
    - All maps, data and model output created for each pilot study area are being provided to the participating agencies along with a final report. Provided materials include a copy of BurnPro program code and associated documentation. Data provided include historical weather, historical ignitions, and coverages of fuels and expected rate-of-

spread. *The review of these study area final reports will be completed by February 11th, 2005.*

  - Final report contains a chapter that serves as a guidebook for replicating the results we obtained using the model BurnPro and/or for conducting additional analyses to explore alternative fire management strategies. *This guidebook represents an* ***addition*** *to the original proposed list of deliverables.*

- Publications

  - Miller, C., B. Davis. Modeling the probability of burning to help evaluate fire use strategies. In preparation. *Due to recasting of objectives (see Goals and Objectives, Chapter 1), the focus of this paper was changed from the proposed topic, which was to evaluate availability of natural ignitions for restoring fire regimes. To be submitted to peer-reviewed journal Spring 2005.*
  - Davis, B., C. Miller. 2004. Modeling Wildfire Probability Using a GIS. In: Proceedings of the ASPRS 2004 Annual Conference, Denver, USA. May 23-28. American Society of Photogrammetry and Remote Sensing (CDROM). *Originally intended for Fire Management Today.*

- Presentations

  - Poster presentation: 2nd International Wildland Fire Ecology and Fire Management Congress, Orlando, FL, November 2003.
  - Poster presentation: National Fire Plan Conference, Reno, NV, February 2004.
  - Oral presentation: Symposium on Science and Monitoring, Denver, CO, September 2004.

  The following presentations represent ***additions*** *to the original proposed list of deliverables*:

  - Invited oral presentation: American Society for Photogrammetry and Remote Sensing, Denver, CO, May 2004.
  - Invited oral presentation: Technical Fire Management, Bothell, WA, October 2004. *Lecture notes and slide presentation were provided in course materials.*
  - Poster presentation: Mixed Severity Fire Regime Conference, Spokane, WA, November 2004.

- Other communication and additional deliverables

  - Two rounds of site visits included presentations to fire and resource management staffs at each of 5 study areas.
  - Site visit and presentation to fire and resource management staff for potential study area (Grand Canyon National Park).
  - "Research in a Nutshell" – a two page synthesis of project findings

- Project website http://leopold.wilderness.net/research/fprojects/F002.htm

All presentations, the published conference proceedings paper, the Nutshell, and a draft of the BurnPro guidebook chapter are provided here in the Appendices. After reviews are completed February 11, 2005, an example of one of the final reports to the study areas will be forwarded to the JFSP office. Similarly, the final draft of the journal article will be forwarded upon submission.

Lessons Learned

Our original intent was to directly compare our probability of burning estimates to historical fire frequencies as a way to determine whether natural ignitions are sufficient for restoring natural fire regimes. We soon realized that it was impossible to make this comparison because our probability of burning estimates are based on a snapshot of current fuel conditions and cannot be compared to historical fire frequencies that occurred under very different (and quite unknowable) vegetation and fuel conditions. Instead we focused on answering "*where are restoration objectives most easily met through the use of natural ignitions, and where are challenges expected to be greatest?*" and worked to identify areas on each landscape that are most influenced by the suppression of fires on adjacent lands. We also originally intended to produce information that would be used to develop fire management plans (FMPs) and delineate WFU zones. However, the study areas available to us already had FMPs with delineated WFU zones. Therefore, we evaluated these FMPs rather than help to design them.

Our approach required substantial data about fire, fuels, and weather, and we selected study areas that met these requirements. From our perspective, there are obvious advantages to using familiar study areas where prior research has developed the required data. However, we note that there is also a tradeoff of lost opportunities to learn from new study areas when we continue to study the same iconic parks and wildernesses time and time again. For example, these areas we selected tend to be those with established FMPs and active WFU programs, and may not represent a full range of management challenges.

Although we selected well-studied sites with excellent data sets, we encountered problems with data availability. For example, we waited several months for new fuels data layers for both Yosemite and Great Smoky Mountains National Parks. If the project time line had been less than 3 years, we may not have been able to accommodate these delays.

Underlying this project is a principle that fires do not necessarily stop at administrative boundaries, and therefore, neither do the impacts of fire management activities. As such, we encourage efforts to look beyond a unit's boundaries when developing fire management plans. Sequoia-Kings Canyon National Park was the only study area for which we had data that extended far beyond a single administrative unit and this is due to the interagency planning efforts of the Southern Sierra Geographic Information Cooperative, previously funded by JFSP. We do recognize that we may have squandered several opportunities to foster interagency cooperation and collaborative planning during this project. In retrospect, we should have invited staff from neighboring management units to share in our discussions during our site visits.

Working in multiple study areas was an advantage because it allowed us to develop a more robust approach. For example, our approach to calculating the probability of burning from two sub-probabilities allowed us to handle sites with different precipitation regimes. However, we found that working in so many study areas posed several logistical challenges. In particular, we underestimated the difficulty we would have with scheduling site visits for so many study areas.

We did not anticipate doing so much model development as part of this project, but we needed to resolve some conceptual issues with BurnPro. These efforts were time-consuming, although we feel they were very worthwhile as they resulted in an improved tool and more meaningful analyses.

The interest in the model BurnPro that was generated during this project gave us additional insight for future applications and has encouraged us to continue developing the model. We did not anticipate this level of interest or the time required to respond to requests for information. The guidebook we developed should reduce reliance on our expertise in the future and allow management staff to conduct additional analyses on their own. A continued concern of ours is how to respond to requests for a tool that is still under development and testing and has not been formally released. We consider any delivery of the tool to date as experimental and have urged caution with using and interpreting the results.

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Chapter 1 Introduction

Purpose and Need

Wildland fire and fuels managers face unique challenges and opportunities on unroaded lands which include more than 105 million acres of federally designated wilderness. Reduced access to the interiors of these areas limit the ability to apply prescribed fire, thinning and other mechanical methods for fuels management. Further, manipulative methods for fuels management may be inappropriate for use in designated wilderness, and are limited by current legal and policy constraints. Current federal interagency fire policies facilitate the use of lightning-caused natural ignitions for wildland fire use (WFU). Unroaded areas and areas managed as wilderness provide unique opportunities for applying WFU as a fuels management strategy while satisfying legal and policy mandates to restore natural or historical fire regimes and ecosystem conditions. But can WFU successfully restore historical fire regimes?

In many wilderness areas, current fuel conditions may preclude the use of wildland fire because of excessive risks to natural resource values within the wilderness or to social values in the adjacent wildland urban interface (WUI). In some areas, especially small wilderness areas with extensive WUI areas, WFU may never be feasible. Even in larger unroaded areas, there will always be an argument to suppress some natural ignitions because of these risks. Ignitions outside of these areas that otherwise would immigrate into wilderness are usually suppressed, further limiting the amount of natural fire that can occur. Before investing limited time and resources in developing and implementing a fire management plan, wildland fire and fuels managers need information and tools to understand where they are most likely to meet management objectives and where to expect their greatest challenges.

This project helped evaluate the feasibility and effectiveness of WFU as a strategy for managing fuels and restoring historical fire regimes. The project directly addressed the research needs described in Task 1 of RFP 2001-1 to "evaluate the impacts of alternative management strategies" (specifically WFU) "on fire regimes in unroaded areas, wilderness areas, and other areas managed for similar purposes." The information produced resulted in "improved understanding of the options for restoring and managing fire in unroaded, wilderness, and similar areas" and provided a "tool for evaluating and understanding management and restoration goals in unroaded, wilderness, and other areas with restricted access."

Project Description

We developed and used an approach to help assess the feasibility of WFU as a strategy for restoring historical fire regimes in wilderness and on other unroaded lands. We used 5 wilderness areas and national parks as study areas to develop our analysis approach, which we used to evaluate the existing fire management plans at each of the study areas. We were particularly interested in evaluating the impact of suppressing ignitions from outside designated WFU zones that otherwise would have immigrated into these areas. Our evaluation identified areas where restoration objectives can be most easily met through the use of natural ignitions. We also identified areas within WFU zones where meeting restoration objectives through the use of natural ignitions alone may be a challenge due to the suppression activities on adjacent lands.

We conducted two rounds of site visits to each study area so that fire management staff could provide input and feedback on our approach and analysis results in the form of expert knowledge. At the request of fire and resource management staff, we provided additional analyses to improve their assessment of the risks and opportunities from WFU.

Goals and Objectives

The goal of this project was to develop an approach to assess the feasibility of wildland fire use (WFU) as a strategy for restoring the process of fire and managing fuels in wilderness and other unroaded lands. With this approach, we sought to directly support the development of new Fire Management Plans

(FMPs) and to help evaluate current FMPs as they apply to wilderness management objectives. There is a common assumption that fire restoration can be achieved in an area if natural ignitions are allowed to burn. But this assumption ignores the contribution of naturally ignited fires that would have immigrated into the area from outside. This study provides a better understanding of the ability of a FMP to achieve its goal of restoring natural fire regimes and provides new information for future FMP revisions.

Our original intent was to develop information about the risks and benefits that could result from naturally ignited fires, and then use this information for FMP development to delineate zones where WFU can be reasonably considered. In those areas where WFU can be considered, we then intended to assess whether there are enough natural ignitions to restore the historical fire frequency. As described below, we modified this original intent and subsequent analysis approach in two ways.

First, the study areas we selected already had approved FMPs with delineated WFU zones. Therefore, we did not develop information to *design* FMPs, but instead we developed information to *evaluate* the existing FMPs. Although we didn't use our analyses of risks and benefits to delineate WFU zones, we did develop these analyses to meet specific requests from managers. Therefore, we did not use the risk-benefit analyses to determine "Where can WFU be considered given the current conditions of fuels in the study area and the risks to ecological and social values both within and outside wilderness or park?" Instead, we used these analyses to improve the assessment of risks and benefits for prioritizing fuels treatments and prevention planning.

Second, when we first proposed this project, we intended to directly compare our probability of burning estimates to historical fire frequencies as a way to determine whether natural ignitions are sufficient for restoring natural fire regimes. However, we subsequently realized that such a direct comparison would not be valid or meaningful. Our probability of burning estimates are based on a snapshot of fuel conditions (in this case current fuels) and are therefore not comparable to historical fire frequencies that occurred under very different (and quite unknowable) vegetation and fuel conditions. We considered developing probability of burning estimates for different historical fuel "scenarios" as a way to work around this fundamental limitation, but discussions with fire management staff convinced us instead to identify areas on the landscape that are most influenced by the elimination of imported fires. Therefore, instead of answering the question "*are there enough natural ignitions to restore the historical fire frequency?*" we focused on answering "*where are restoration objectives most easily met through the use of natural ignitions, and where are challenges expected to be greatest?*"

As such, our primary research objective was to determine how well we can expect current or proposed WFU strategies to achieve the restoration of natural fire regimes. We hoped to answer the following questions:

- How does suppression of lightning-caused ignitions that occur *outside* WFU zones affect our ability to achieve the restoration of fire *inside* the WFU zones? In other words, what is the effect of eliminating the importation of fires that start on adjacent lands?
- Where eliminating the importation of fires appears to pose the greatest challenges for achieving restoration objectives, what are some management alternatives?

A secondary objective was to evaluate the risks and opportunities from WFU fires. We assessed the risk and opportunity that lightning ignitions from the WFU zone might pose to different values of interest in the study area. We evaluated risks to areas such as the WUI or and ecologically sensitive areas, and we evaluated expected benefits to areas that are inhabited by fire-dependent species. This information can help with prevention planning, prioritizing fuel treatments, and anticipating where to expect the greatest conflicts with other management objectives when implementing a WFU program.

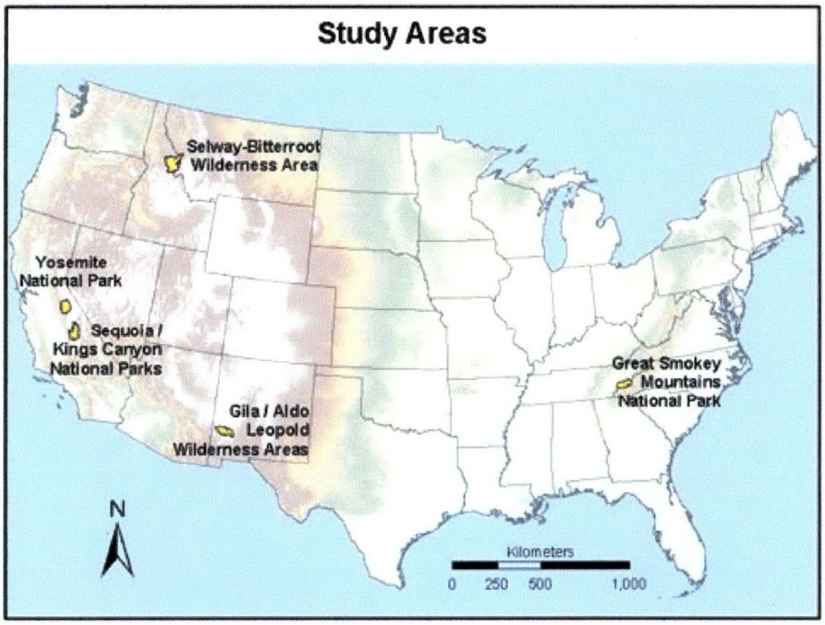
Chapter 2 Study Areas

Site Selection

Study sites were selected for the availability of fire history and fuels information, local expertise, and for prior collaborative relationships that we had with managers and other cooperating researchers. In addition, we sought to include study areas that had management challenges that we could help address through meeting our project objectives. Most of the study areas we selected had experienced a relatively large number of fires in the 20th century and therefore provided important data for validating the modeling component of this project. The most important factor that drove our study area selection was the availability of fuels and fire data. We settled on 5 high quality study areas that met our criteria (Figure 1): Gila/Aldo Leopold Wilderness, Great Smoky Mountains National Park, Selway-Bitterroot Wilderness, Sequoia-Kings Canyon National Parks, and Yosemite National Park. Selection of Great Smoky Mountains National Park was a direct response to the JFSP Governing Board's request to include a site in the eastern US. All five study areas had existing Fire Management Plans with designated WFU zones.

Other eastern sites we explored were Everglades National Park and Okeefenokee National Wildlife Refuge. However, after discussions with resource and fire management staff from these two units, we decided not to include these study areas in this project. We felt that our project objectives were not a good fit for the management challenges facing these units. In addition, the fire regime characteristics at both these sites are considerably different from our other mountainous forested study areas, and we were not confident that our modeling approach would adequately represent these sites.

Figure 1. Location of project study areas.

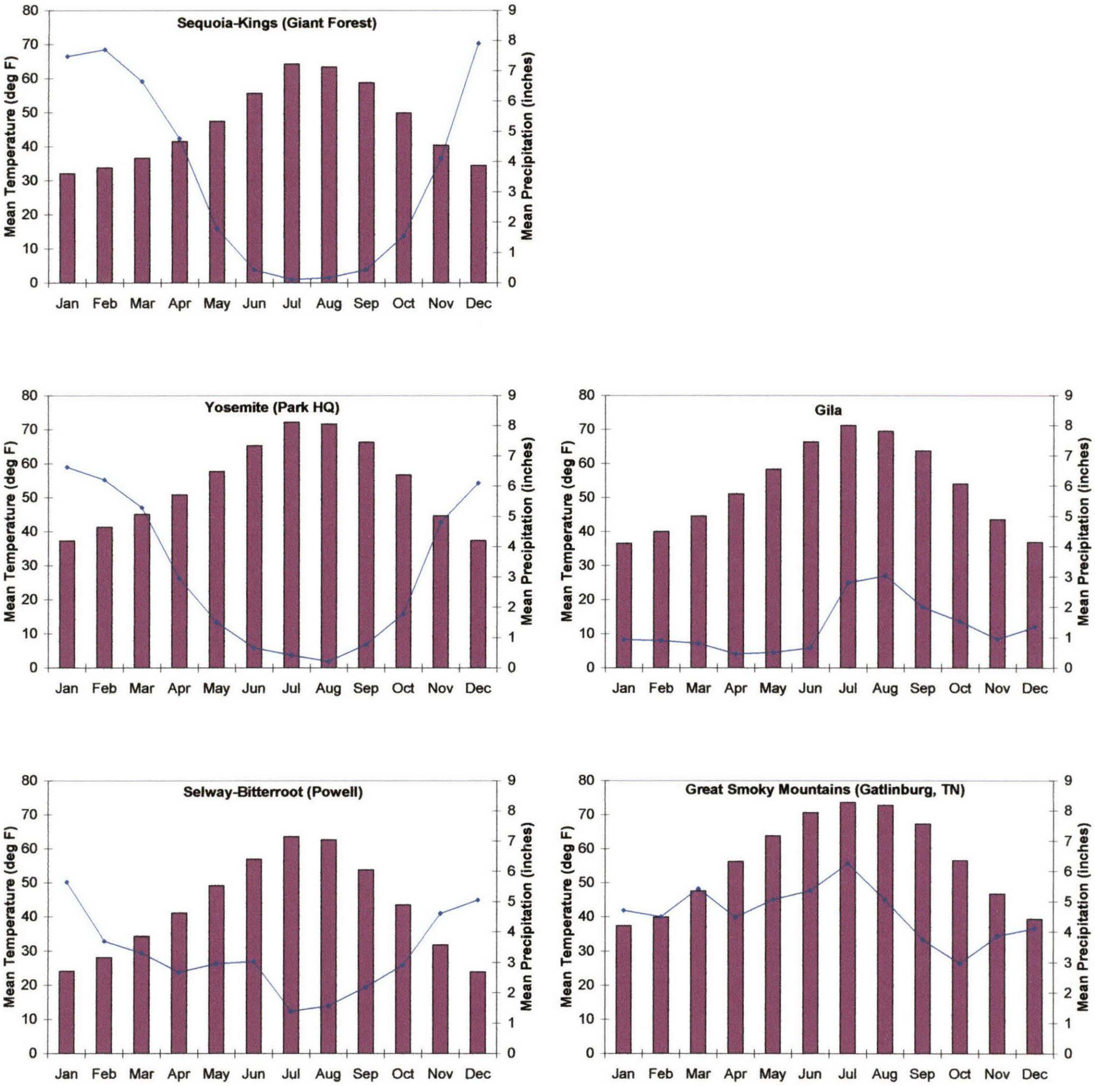

Study Areas
Selway-Bitterroot Wilderness Area
Yosemite National Park
Sequoia / Kings Canyon National Parks
Gila / Aldo Leopold Wilderness Areas
Great Smokey Mountains National Park
N
Kilometers
0
250
500
1,000

We originally proposed to include Glacier National Park as a study area because of expected collaboration with a proposed project with Dr. Michael Medler. However, because that project was not funded, those collaborative opportunities did not materialize. We considered Grand Canyon National Park as a sixth study area, but due to staffing changes at the park, we had difficulty coordinating with their staff and obtaining the required data in a timely manner. To avoid further delays with the project, we decided not to pursue this study area.

In addition to our five formal study areas, we had two “ad hoc” study areas where portions of our analysis approach were used and demonstrated. The first was the Bitterroot National Forest, adjacent to and part of the Selway-Bitterroot Wilderness and was done as part of JFSP project #99-1-3-16. The second was the Cloud Peak Wilderness in northeastern Wyoming, where, in response to a request from fire management staff, we experimentally released a development version of the BurnPro model and preliminary documentation of our procedures.

Distribution of precipitation is a key difference among our five study areas (Figure 2) and the study areas will be described for the following precipitation patterns: Summer-dry, Summer-monsoon, and Summer-moist.

Figure 2. Annual precipitation and temperature patterns for the five study areas.



Summer-Dry

Sequoia-Kings Canyon National Parks, Yosemite National Park and the Selway-Bitterroot Wilderness fall into the summer-dry category. These study areas have relatively cool moist winters and warm dry summers with most annual precipitation occurring outside the summer months. Therefore, during the growing season, plants are largely dependent on water that is stored in the form of snow or deep in the soil. As can be seen in Figure 2, the pattern in Sequoia-Kings Canyon and Yosemite is very dramatic with virtually no precipitation at all during

July and August. The Selway-Bitterroot has a similar, albeit less pronounced, pattern.

Sequoia-Kings Canyon National Parks are located on the western slope of the Sierra Nevada in central California. Combined acreage for these two parks is 349,500 ha (863,300 acres). Elevations range from (420 to 4410 m (1380 to 14,470 feet). Vegetation ranges from the foothill grassland and chaparral, through ponderosa pine, to the mixed conifer zone, to red fir and lodgepole pine and finally to high elevation pine near treeline. Generally, fire frequency increases toward drier environmental positions, and as fire frequency increases, fire severity tends to decrease (Caprio and Swetnam 1995). Lightning is most common on higher elevations, but can still be significant at lower elevations. In the past, lightning ignitions may have been supplemented by burning by native Americans and by sheepherders during the late 1800s. Fire suppression since the early 1900s has disrupted the fire regime allowing dead fuel to accumulate and understory tree density to increase. Currently, the fire and fuels management program at the Parks seeks to restore and maintain the natural fire regime in a manner consistent with firefighter and public safety. This program includes the use of prescribed fire, managing unplanned fires for the benefit of ecological values, and fire suppression. Because Sequoia-Kings Canyon has been actively involved with interagency fire management planning (Southern Sierra Geographic Information Cooperative; JFSP project # 99-1-3-04), we extended our analysis beyond Park boundaries and used the watershed boundaries that this planning effort has adopted. Our study area is the Kings and Kaweah watersheds, a very large landscape (782,700 ha; 1,932,600 acres) managed by multiple agencies including the US Forest Service, Bureau of Land Management, and state and local governments.

Yosemite National Park is approximately 100km north of Sequoia-Kings Canyon National Parks. It is 303,000 ha (750,000 acres) in size and ranges in elevation from 660-3950m (2100-13000 feet). Vegetation in Yosemite is similar to that in Sequoia-Kings Canyon, but Yosemite has less foothill and low elevation vegetation. Fire regimes and the history and management of fire in Yosemite is also similar to that of Sequoia-Kings Canyon NPs. Seventy-five percent of the park is managed to allow wildland fires to burn in a prescribed natural fire zone with another 8% in a conditional zone where fires have been allowed to burn under some conditions.

The Selway-Bitterroot Wilderness is located on the border of north-central Idaho and western Montana. We buffered the 0.5 million-hectare (1.2 million-acre) designated Wilderness to obtain a study area of 1.1 Mha (2.7 M acres). Elevations range from 430-3070 m (1410 to 10,060 feet). The climate ranges from inland-maritime in the northwestern part of the Wilderness to a continental rain shadow climate in the southern and eastern portions (Finklin 1983). The vegetation ranges from open stands of ponderosa pine at lower elevations, to mixed conifer forests at intermediate elevations, to whitebark pine, alpine larch, and Engelmann spruce at higher elevations (Habeck 1976). The area experiences a mixed severity fire regime: many fires are nonlethal surface fires but under suitable weather and fuel conditions, lethal surface fires and even stand replacing crown fires occur (Brown et al. 1994). The fire season typically runs from late June to mid-September; during this time, lightning-caused fires accompany frequent thunderstorms. Within the wilderness boundary, unplanned ignitions are often allowed to burn, although if a threat is perceived to the wildland-urban interface outside the wilderness, fires within the wilderness will be controlled (Law et al. 1997).

Summer Monsoon

The Gila-Aldo Leopold Wilderness in west-central New Mexico experiences a summer monsoonal precipitation pattern. Annual precipitation is low, and a rainy season typically begins at the end of July. We buffered the 226,000 ha (558,000 acre) Gila Wilderness and 81,800 ha (202,000 acre) Aldo Leopold designated Wildernesses to obtain a study area of 576,000 ha (1.4 M acres). The area ranges in elevation from 1380m to 3310m (4,510 to 10,860 feet) and features steep mountains, rough deep canyons, flat mesas, large river channels and flood plains. Vegetation ranges from desert scrub at the lowest elevations, through pinon-juniper woodlands and ponderosa pine and Douglas fir forests at middle elevations, to subalpine forests at the highest elevations. Fire management objectives are to return fire to its natural role in the wilderness ecosystem to the maximum extent possible, consistent with safety of persons, property, and other resources. The risks and consequences of wildland fire within wilderness, or escaping from wilderness are to be reduced to an acceptable level. The Gila National Forest, which manages these wilderness areas, experiences the highest fire occurrence nationwide. In the 10 year period from 1988 to 1998, approximately 67,923 ha (167,711 acres) have been managed with the use of fire.

Summer-moist

The Great Smoky Mountains National Park falls into the category of summer-moist. Annual precipitation is approximately 140 cm (55 inches), and is evenly distributed throughout the year. There is no dry season to speak of, although the warm temperatures of the summer months create more evapo-transpirative demand for plants. Stretching over 200,000 hectares (493,800 acres)of the Southern Appalachian Mountains, Great Smoky Mountains National Park is one of the largest protected areas in the eastern US. A primary goal of park management is to preserve the native plants and animals found in the park. In order to do so, it is necessary to preserve the natural processes that perpetuate them, including fire. To help counteract the negative impacts of fire exclusion the park has adopted a number of new fire-related policies. These include recognizing the role of naturally ignited wildfire in maintaining the health of Southern Appalachian ecosystems, establishing the management practices which include WFU, in which naturally ignited wildfires are allowed to burn in designated areas under prescribed conditions. Although the fire season is approximately 10 months long, natural ignitions tend to occur April through August.

In addition to being our only eastern US study area, it was our only site with extensive deciduous forest, which means that fire behavior fuel models must include "leaf-off" and "leaf-on" versions. Fuels data were originally developed by researchers at the University of Georgia for the leaf-off condition, which accurately represents fuels from approximately mid-October through mid-April. As such, it was necessary to adapt the leaf-off fuel models to approximate leaf-on conditions.

Chapter 3 Methods

To assess the feasibility of WFU as a strategy for restoring historical fire regimes, the frequency and location of ignitions, as well as their likelihood for spreading, must be evaluated. We used a GIS-based approach to estimate the probability of burning for every location on a landscape (Davis and Miller 2004, Miller 2003). For the WFU zones identified in Fire Management Plans, we estimated the probability of burning based on all natural ignitions in the study area. Ignitions falling outside of approved WFU zones were removed from the analysis and the probability of burning was recomputed. From these analyses we quantified the effect of eliminating the importation of fires that start on adjacent lands. We also combined the information on probability of burning with information on resource values to improve assessments of risks and benefits.

This section briefly describes the GIS model and the analyses we conducted to evaluate FMPs and to identify risks and opportunities for WFU. Detailed description of an earlier prototype of the GIS model is available in the literature (Miller 2003). A description of the version we used for this project is provided in Davis and Miller (2004) (see Proceedings Paper, Appendix A), in lecture notes (see Technical Fire Management, Appendix B) and is currently being prepared for a peer-reviewed journal article. Finally, detailed procedures for data development and running BurnPro are included as a guidebook in a chapter in the final reports to each study area (see Guidebook, Appendix A).

Probability of Burning

Information on where fire is most likely to occur within a landscape is valuable for assessing risk, prioritizing fuel treatments and prevention planning. Planning for WFU is also aided with an understanding of where the most frequent opportunities for WFU are within a landscape as this information can be used to develop fire management plans and to support the go/no-go decision.

Probability of burning is not the same as probability of ignition. Several regional assessments have derived and used probability of ignition, whereby the number of ignitions per unit area is computed for a particular time period (e.g., Northern Region Cohesive Strategy, http://www.fs.fed.us/r1/cohesive_strategy/datafr). Information about probability of ignition is very useful for assessing risk at a coarse scale, but it is not very useful finer scales such as the mid-scale and/or project level. Probability of burning depends on the probability of ignition, but it also depends on how fire spreads in a spatial context. The methods we developed for estimating probability of burning are intended to help with planning at the mid scale and/or project level.

Probability of burning as we define it here is also different from probabilities generated in RERAP. RERAP is a non-spatial analysis tool applicable to a single fire incident (FRAMES 2003). The probability of burning that we derive and use to evaluate fire management plans represents the cumulative probability of many events, averaged over many years. The intended planning horizon (several years to decades) is different from RERAP's single incident timeframe.

BurnPro

BurnPro is a GIS model that estimates the annual probability of burning for every pixel on a raster landscape (Davis and Miller 2004, Miller 2003) and considers ignitions, rate of fire spread, time available for fire spread, and topography, all in a spatial context. BurnPro uses topography, historic weather, current fuel model data and historic ignition locations to estimate the likelihood of burning given the speed and direction a fire might spread from any ignition point. It computes the probability of burning for each pixel as the product of two "sub-" probabilities: 1) the probability that fire reaches the location before the *end of the fire season* (*PEnd*) and 2) the probability that fire will reach the location before a *fire-stopping event* (*PStop*). As such, it integrates the timing and location of ignitions, rate of spread of fire (as it is affected by fuels, topography and weather), length of fire season as it varies over elevation, and frequency of fire-stopping events (i.e., rain) during the fire season.

What BurnPro does:

- Provides an estimate of *average annual probability* of burning for every cell on a raster landscape using data from many years and multiple events that would occur under a range of weather conditions.
- Generates *continuous* values (not categorical).
- Although BurnPro generates numerical values representing probability, these should be interpreted only as *relative* values.

Several GIS data layers are required to run BurnPro, and developing some of these requires the use of other analysis tools:

- Monthly ignition point coverages. These data are commonly available from http://famweb.nwcg.gov/weatherfirecd

- Rate-of-spread and direction-of-maximum-spread grids for selected percentile weather conditions. Rate-of-spread and direction-of-maximum-spread grids are generated from FlamMap (http://fire.org/nav.mas?pages=flammap&mode=1). Percentile weather conditions are determined using Spread Component Index generated from FireFamilyPlus (Bradshaw and McCormick 2000).

- Elevation (m) grid, e.g., from a digital elevation model (DEM).

- Average length-of-fire-season grid. This can be derived in a number of ways, including using Daymet variables like growing-degree-days (http://daymet.org), using drought-days computed by FACET (Urban et al. 2000), or simply by using expert judgment about how fire season varies across the landscape.

BurnPro also requires some information about rain and wind:

- Frequency of fire-stopping precipitation events, by month. The average monthly frequency of fire-stopping events can be determined using FireFamilyPlus (Bradshaw and McCormick 2000). These events might be defined as a certain amount of rain within a given time period (e.g., 0.5 inches of rain within a 5-day period).

- Frequency distribution of wind directions. Daily observations of wind directions can be analyzed using a simple spreadsheet program like Excel to determine the relative proportion of observations falling into 8 compass directions.

BurnPro is intended to support long-term processes such as fire management planning. It is not suitable for most incident management applications, but can be useful for the type of pre-planning that supports a go/no-go decision. For more details on BurnPro, please see materials in Appendix A, including the conference proceedings paper as well as lecture notes describing the approach.

Key Variables

Historical weather data. We used data from representative weather stations for each study area (Table 1). In an attempt to capture the weather of the study area as a whole, we sought data from multiple stations across a representative range of elevations. In the case of Yosemite, however, data from only one weather station (Crane Flat) were used, due to anomalies in the data from other potential weather stations. This one station, which falls near the average elevation for the park, was judged to be representative by the fire use specialist who uses data from this station for fire behavior modeling in Yosemite.

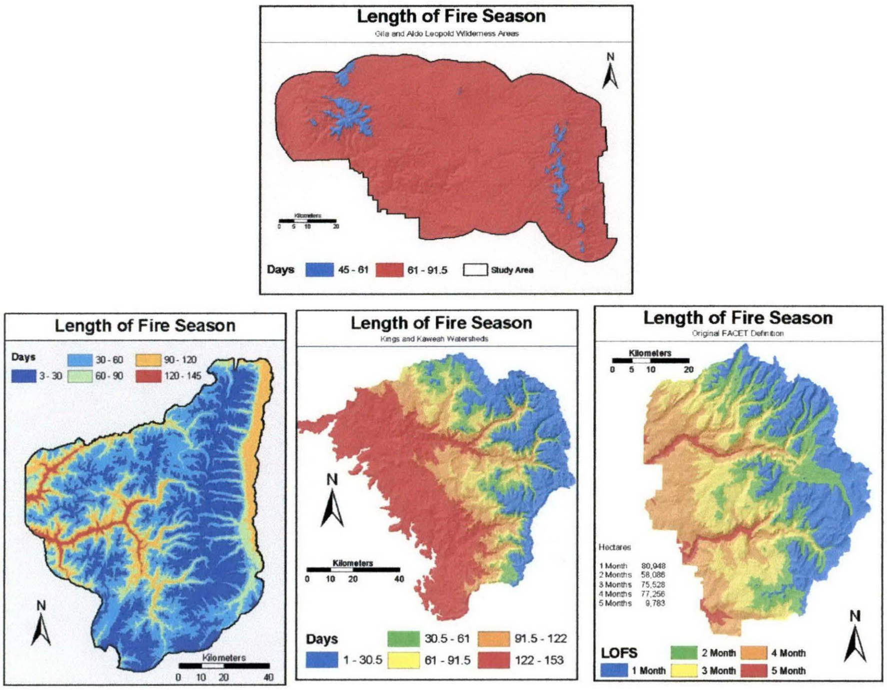
Table 1. Sources for historical weather data

Study Area	Weather Station	Elev (m)	# Years	Period of Record
Gila/Aldo Leopold	Bearwallow	3034	10	1994-2003
	Beaverhead	2043	29	1975-2003
	Gila Center	1738	29	1975-2003
Great Smoky Mountains NP	Cherokee	1037	12	1989, '91-'94, '96-'97, '99-2003
	Indian Grave	823	12	1989, '91-'94, '96-'97, '99-2003
Selway-Bitterroot	Hell's Half Acre	2474	29	1975-2003
	Moose Creek	750	29	1975-2003
	Powell	1039	29	1975-2003
	Westfork	1338	29	1975-2003
Sequoia-Kings Canyon NP	Ash Mountain	518	26	1977-2002
	Park Ridge	2299	26	1977-2002
	Pinehurst	1238	26	1977-2002
Yosemite NP	Crane Flat	1850	21	1979-1999

Length of fire season. Longer periods of time available for fire to spread should lead to higher probability of burning. This length of time—the length of fire season—varies across a landscape according to elevation, aspect, topographic position, etc. In this project, we accounted only for variation with elevation. Although we used a fairly complicated soil-water-balance model (Urban et al.

2000) and its estimates of "drought-days" for different elevations to approximate how length of fire season varies with elevation, there are many other possible ways to map fire season across the landscape. For example, estimates of growing-degree-days from Daymet (http://daymet.org) could be used as a proxy for length of fire season, or expert knowledge/opinion of the area could be used.

Figure 3. Length of fire season derived from drought-day estimates by a soil-water-balance model (Urban et al. 2000) for Gila/Aldo Leopold Wilderness (top center), Selway-Bitteroot Wilderness (bottom left), Sequoia-Kings Canyon NP (bottom center), and Yosemite NP (bottom right). Note: Length of fire season does not vary in Great Smoky Mountains NP for the months modeled (April-August) as they are a subset of the overall fire season (February-November).


Length of Fire Season
Gila and Aldo Leopold Wilderness Areas
N
Kilometers
0 5 10 20
Days 45 - 61 61 - 91.5 Study Area
Length of Fire Season
Days 3 - 30 30 - 60 60 - 90 90 - 120 120 - 145
N
Kilometers
0 10 20 40
Length of Fire Season
Kings and Kaweah Watersheds
N
Kilometers
0 10 20 40
Days 1 - 30.5 30.5 - 61 61 - 91.5 91.5 - 122 122 - 153
Length of Fire Season
Original FACET Definition
Kilometers
0 5 10 20
Hectares
1 Month 80,948
2 Months 58,086
3 Months 75,528
4 Months 77,256
5 Months 9,783
N
LOFS 1 Month 2 Month 3 Month 4 Month 5 Month

Frequency of fire-stopping precipitation events. Less frequent heavy rain events should lead to higher probability of burning. We used the FireFamilyPlus event locator and historic weather data to determine number of times the area experiences a fire-stopping rain event (Table 2). In all but one of our study areas, we defined a fire-stopping event as an occurrence of more than 0.5 inches of rain within a 5-day period. In Great Smoky Mountains National Park, we defined a fire-stopping event as 1.5 inches of rain within a 5-day period.

Table 2. Number of fire-stopping rain events

Study Area	Apr	May	Jun	Jul	Aug	Sep	Oct
Gila/Aldo Leopold	–	0.33	0.68	2.23	–	–	–
Great Smoky Mtns NP	1.72	1.49	1.90	1.48	0.98	–	–
Selway-Bitterroot	–	–	2.43	1.29	1.40	1.25	–
Sequoia-Kings Cyn NP	–	–	0.21	0.06	0.04	0.40	0.66
Yosemite NP	–	–	0.49	0.21	0.11	0.99	0.60

Ignitions. A higher frequency or density of ignitions should lead to higher probability of burning. Furthermore, ignitions that occur early in the season have a longer opportunity to burn. Therefore, all other factors being equal, the more ignitions occurring early in the season should lead to a higher probability of burning. Historic ignition data are available from http://famweb.nwcg.gov/weatherfirecd. These data contain geographic location (latitude/longitude), date, and cause (e.g., lightning- or human-caused). We separated these point datasets by month of occurrence and imported them into a GIS database. From these monthly point coverages, we calculated ignition densities using the POINTSTATS function in ArcInfo (ESRI 1998) and created up to 5 density grids to represent low to high density classes for each month of occurrence (Figure 4). For example, if there were 4 months in the fire season (e.g., June-September) and 5 density classes, the result was 20 ignition grids. Separating the data by density class allows BurnPro to weight results when calculating the average annual probability of burning (the last step in the BurnPro approach). Weights are assigned according to frequency of occurrence (i.e., density of ignitions). For example, probabilities generated using density class 5 are weighted 5 times more heavily than those generated using density class 1. We used 15 years or more of ignition data, and usually started with data from 1986 because spatial location accuracy before 1986 is generally very poor (Table 3).

Figure 4. Lightning ignitions and corresponding ignition density grid for the Gila/Aldo Leopold Wilderness.

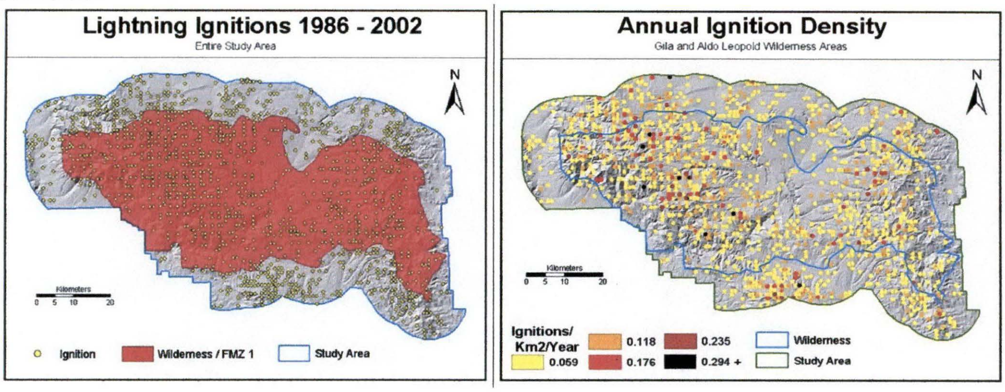

Lightning Ignitions 1986 - 2002
Entire Study Area
N
Kilometers
0 5 10 20
Ignition
Wilderness / FMZ 1
Study Area
Annual Ignition Density
Gila and Aldo Leopold Wilderness Areas
N
Kilometers
0 5 10 20
Ignitions/ Km2/Year
0.059
0.118
0.176
0.235
0.294 +
Wilderness
Study Area

Table 3. Lightning ignition data

Study Area	# Ignitions (entire study area)	# Ignitions (WFU zone only)	#Years	Period of Record
Gila/Aldo Leopold	1721	1044	17	1986-2002
Great Smoky Mtns NP	34	27	17	1986-2002
Selway-Bitterroot	2888	1221*	17	1986-2002
Sequoia-Kings Cyn NP	952	184	19	1981-2000
Yosemite NP	720	529	17	1986-2002

*Ignitions in the Selway-Bitterroot WFU zone include all from the Interior zone plus ignitions after July from the Early Season/Drought zone.

Rate- of-spread (ROS). Rapid fire spread should lead to higher probability of burning. We used FlamMap to calculate rate-of-spread (ROS). FlamMap provides a snapshot of expected fire behavior for every pixel on a raster landscape based on current fuels, slope, aspect, fuel moistures conditioned under specified weather conditions, and constant wind. Because FlamMap calculates ROS for static conditions, we made multiple runs to account for potential fire spread under a variety of weather conditions and wind direction. As such, we ran FlamMap multiple times to represent ROS under 8 different wind directions and 4 different percentile weather categories (Table 4). Percentile weather categories were determined using the Spread Component (SC) index (Bradshaw et al. 1983). For example, to account for 8 wind directions (N, NE, E, SE, S, SW, W, NW) and 4 weather categories (low: 0-79% SC, moderate: 80-89% SC, high: 90-97% SC, extreme: 98-100% SC), we ran FlamMap to create

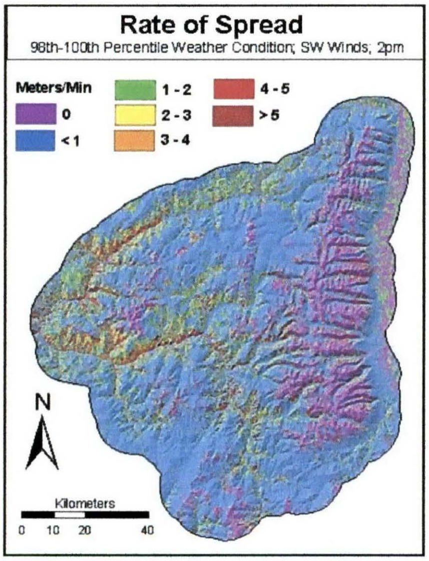
32 ROS grids (Figure 5). The frequency distribution of the 8 wind directions and the percentiles for the weather classes are used by BurnPro to weight the probability results accordingly when the annual average is computed (e.g., note that a 99th percentile weather condition occurs only 1% of the time).

Table 4. Definition of percentile weather categories

Study Area	Low	Moderate	High	Extreme
Gila/Aldo Leopold	0-79	80-89	90-97	98-100
Great Smoky Mtns NP	0-41	42-92	93-98	99-100
Selway-Bitterroot	0-79	80-89	90-97	98-100
Sequoia-Kings Cyn NP*	0-14	15-89	90-97	98-100
Yosemite NP	0-79	80-89	90-97	98-100

* Categories for Sequoia-Kings Canyon NP were defined by the SSGIC planning effort.

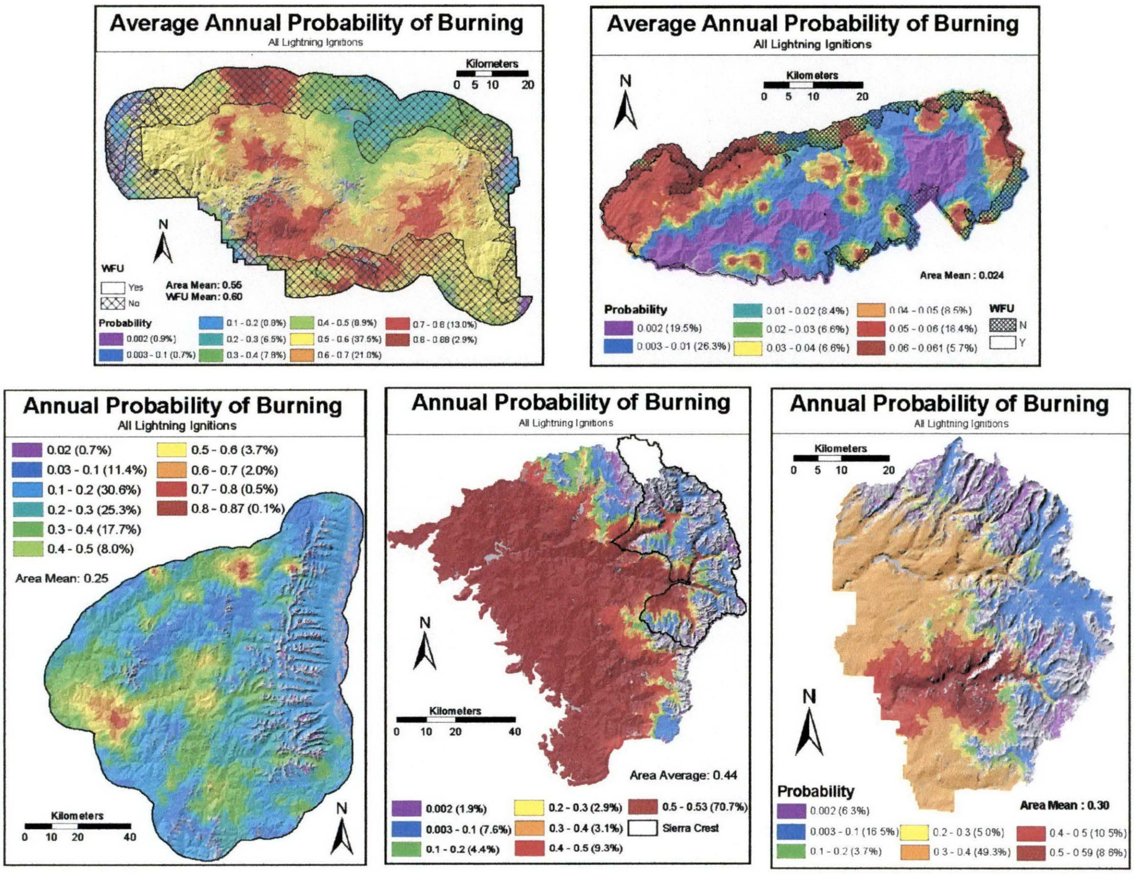
Figure 5. One of 32 rate-of-spread grids for the Selway-Bitterroot Wilderness representing rate-of-spread under the extreme weather category and southwest winds.



Cumulative spread time (CST). The longer it takes fire to reach a location, the lower the probability of burning should be. To compute the number of days for fire to spread from ignition locations to all other points on the landscape, BurnPro uses the ArcInfo function Pathdistance (ESRI 1998). Pathdistance is a least-accumulative cost spreading algorithm that computes the *cheapest* path and *total cost* of traveling to each cell in a grid. Instead of *cost*, we are interested in *time*. BurnPro uses Pathdistance to find the path of least resistance across the landscape and to compute the total time it takes to travel that path. Pathdistance requires a Source grid and a Cost grid. In BurnPro, the Source grid is one of the ignition density grids and the Cost grid is Time, which is derived from any one of the ROS grids with simple arithmetic. For any pixel on the raster landscape, there are almost an infinite number of paths that fire could take to get there but there is only one *quickest* path--the path that results in the lowest cumulative spread time (CST). BurnPro uses the algorithm in ArcInfo's Pathdistance function to generate CST grids for each unique combination of ignition (source) grid x Time (cost) grid. If there were 20 ignition grids (4 months x 5 density classes) and 32 Time grids (derived from 32 ROS grids), 640 CST grids were generated (20 ignition grids x 32 Time grids).

BurnPro computes the probability of burning for each pixel as the product of two "sub-" probabilities: 1) the probability that fire reaches the location before the *end of the fire season* (*PEnd*) and 2) the probability that fire will reach the location before a *fire-stopping event* (*PStop*). Both *PEnd* and *PStop* depend on knowing how long it would take fire to spread to a location, and therefore both are computed using CST. To compute *PEnd*, CST is compared to the length of fire season. Currently, the Weibull function is used for this: *PEnd* = $\exp[-(\text{CST/season length})^{\eta}]$ where η is a parameter derived from the distribution of season lengths and reflects the interannual variation in season length. To compute *PStop*, CST is essentially compared to the average length of time between fire-stopping rain events. Each of the CST grids is used to compute these two sub-probabilities, which are then multiplied together to derive the annualized probability of burning (Figure 6). The annual distribution of precipitation for the study area determines whether *PEnd* or *PStop* dominates the computation for average annual probability of burning. In Summer-wet and summer-monsoon areas, *PStop* tends to dominate the computation for probability of burning. In summer-dry, *PEnd* is dominant.

Figure 6. Average annual probability of burning for Gila/Aldo Leopold Wilderness (top left), Great Smoky Mountains National Park (top right), Selway-Bitterroot Wilderness (bottom left), Sequoia-Kings Canyon National Park (bottom center), and Yosemite National Park (bottom right).


Average Annual Probability of Burning
All Lightning Ignitions
Kilometers
0 5 10 20
N
WFU
Yes
No
Area Mean: 0.55
WFU Mean: 0.60
Probability
0.002 (0.9%)
0.003 - 0.1 (0.7%)
0.1 - 0.2 (0.8%)
0.2 - 0.3 (6.5%)
0.3 - 0.4 (7.8%)
0.4 - 0.5 (8.9%)
0.5 - 0.6 (37.5%)
0.6 - 0.7 (21.0%)
0.7 - 0.8 (13.0%)
0.8 - 0.88 (2.9%)
Average Annual Probability of Burning
All Lightning Ignitions
N
Kilometers
0 5 10 20
Area Mean : 0.024
Probability
0.002 (19.5%)
0.003 - 0.01 (26.3%)
0.01 - 0.02 (8.4%)
0.02 - 0.03 (6.6%)
0.03 - 0.04 (6.6%)
0.04 - 0.05 (8.5%)
0.05 - 0.06 (18.4%)
0.06 - 0.061 (5.7%)
WFU
N
Y
Annual Probability of Burning
All Lightning Ignitions
0.02 (0.7%)
0.03 - 0.1 (11.4%)
0.1 - 0.2 (30.6%)
0.2 - 0.3 (25.3%)
0.3 - 0.4 (17.7%)
0.4 - 0.5 (8.0%)
0.5 - 0.6 (3.7%)
0.6 - 0.7 (2.0%)
0.7 - 0.8 (0.5%)
0.8 - 0.87 (0.1%)
Area Mean: 0.25
Kilometers
0 10 20 40
N
Annual Probability of Burning
All Lightning Ignitions
N
Kilometers
0 10 20 40
Area Average: 0.44
0.002 (1.9%)
0.003 - 0.1 (7.6%)
0.1 - 0.2 (4.4%)
0.2 - 0.3 (2.9%)
0.3 - 0.4 (3.1%)
0.4 - 0.5 (9.3%)
0.5 - 0.53 (70.7%)
Sierra Crest
Annual Probability of Burning
All Lightning Ignitions
Kilometers
0 5 10 20
N
Probability
0.002 (6.3%)
0.003 - 0.1 (16.5%)
0.1 - 0.2 (3.7%)
0.2 - 0.3 (5.0%)
0.3 - 0.4 (49.3%)
0.4 - 0.5 (10.5%)
0.5 - 0.59 (8.6%)
Area Mean : 0.30

Key Assumptions

All models are built with underlying assumptions and the appropriate interpretation of model output requires an understanding of these assumptions. The most critical assumptions in BurnPro are mentioned here.

- The values in BurnPro's output grids represent average annual probability of burning. The probability of any event can range from 0 (certain it won't occur) to 1 (certain it will occur). For display purposes, the numbers output by BurnPro are converted to percentages and can range from 0.2 to 100%. Although BurnPro generates numerical values representing probability, these should be interpreted only as *relative* values. They do not represent absolute probabilities. It is appropriate to interpret a value of

0.50 as being 5 times greater than a value of 0.10, but a value of 0.50 should *not* be interpreted as indicating a 50 percent chance of burning.

- Estimates from BurnPro are based on long-term ignition and weather patterns and therefore should be used for *long-term planning* efforts rather than being interpreted for short-term purposes.

- The ROS spread grids that BurnPro uses to derive Cumulative Spread Time, and thus *PEnd* and *PStop*, are generated using maps of *current fuels*. The output from BurnPro does not take into account changes in fuels over time due to vegetation succession or disturbances. Because the probabilities represent the probability of burning given current fuels, these estimates are meaningful only so long as the underlying fuel data are valid.

- Rate-of-spread (ROS) calculations are based on twice-daily averages of ROS at 4am and 2pm. The impacts of weather variability at shorter time scales (e.g. a 2-hour wind event) are therefore not represented by BurnPro.

- Calculations by ArcInfo's Pathdistance algorithm are very dependent on how the ignition sources in the Source grid are distributed in space. If ignitions are close together in space, the least accumulative cost-distance paths derived by Pathdistance will tend to be quite short, CST values will tend to be low, and probability of burning will be high. Conversely, if ignitions are spread out widely in space, the paths will be long, CST values will be high and probability of burning will be low. Therefore, the length of the record used for historical ignitions will likely have an influence on BurnPro output, with longer records providing more ignition sources for the Pathdistance algorithm. Running BurnPro using randomly located ignitions instead of historical locations is a useful exercise for better understanding this influence.

- Ignitions are handled on a monthly basis and calculations of probability are based on the assumption that ignitions occur mid-month.

- Probability estimates near the edge of the study area are less reliable than those in the interior. This effect occurs because estimates near the edge can't account for the influence of ignitions outside the study area.

- The length of fire season used represents an average year. In extreme years, ignitions could occur in areas that aren't "in-season" in a normal year. BurnPro ignores ignitions that fall outside the season in a normal year.

- Historic weather data from one or a few weather stations are extrapolated to a large area.

- BurnPro's estimates are only as good as the quality of the input data. The better (more accurate, longer periods of record etc.) the input data the better the estimates of probability of burning.

Expert Knowledge

We conducted two rounds of site visits to our study areas. In the first round of site visits, we relied on fire management staff to identify data sets and parameters to use as input to the model BurnPro. We also learned where the most important values at risk are, and where lightning ignitions are, or are not, likely to be considered for WFU.

During the second round of site visits, we presented our analyses, obtained feedback, and took requests for additional analyses from management staff. In some cases, these additional analyses included revising the WFU zones to represent potential FMP revisions. In other cases, staff requested revisions to the WFU zones to more accurately reflect 'on the ground' realities that are not represented in the FMP. During the second site visit, we also discussed our estimate of expected burn probability with their expectations for achieving fire management objectives. In at least one case (Great Smoky Mountains National Park), it was clear that stated fire and land management goals are not achievable with lightning ignitions.

Evaluating Fire Management Plans

We used the model BurnPro to evaluate the risks, opportunities and challenges for WFU management in Great Smoky Mountains National Park. In particular, we used BurnPro to estimate the probability of burning from *all* lightning ignitions within the entire study area and compared this with the probability of burning from only potential WFU ignitions in areas where WFU is authorized in the Fire Management Plan (Table 5). By examining the difference between these two estimates, we highlighted places in the WFU zones where a natural fire regime would be dependent upon immigration of fires from outside the area. Through this comparison we identified those areas that are not likely to experience as much fire under current fire management strategies as they would under a natural fire regime. We used strategies outlined in the Fire Management Plan along with feedback from local managers to define potential WFU ignitions and the parameters necessary to run BurnPro for these analyses.

Table 5. Number of lightning-caused ignitions used to evaluate FMPs

	Size (hectares)		Total Lightning Ignitions (#)[†]	
Study Area	**Entire Study Area**	**WFU Zone**	**Case 1 ("natural")**	**Case 2 ("current FMP")**
Gila/Aldo Leopold	576,000	313,000	1721	1044
Great Smoky Mtns NP	219,000	175,000	34	27
Selway-Bitterroot *	1,098,000	499,000	2888	1221
Sequoia-Kings Cyn NP	722,000	169,000	952	184
Yosemite NP	303,000	251,000	720	529

*The Selway-Bitterroot WFU zone is defined as the Interior zone plus the Early Season/Drought zone. WFU Zone ignitions include all lightning ignitions from the Interior Zone and only late season ignitions from the ES/D zone.

[†] Lightning ignition counts reflect 17 years of data, except for Sequoia-Kings Canyon, where they reflect 19 years.

Identifying Risks and Opportunities

In addition to our evaluation of Fire Management Plans, we took a more direct look at some of the risks and opportunities of WFU. These analyses varied among the study areas according to values-at-risk for each site and to site-specific requests.

Our estimates of average annual probability of burning were overlaid with several values-at-risk to improve risk assessments. The estimates of probability of burning were also examined to determine where the greatest opportunities for WFU are. By overlaying our estimates with values-to-benefit, we identified where WFU is most likely to *benefit* specific resources.

Chapter

4

Results

We used estimates of probability of burning to determine how well current or proposed WFU strategies might be expected to achieve the restoration of natural fire regimes. In particular, we used these analyses to evaluate how, and where, suppression of lightning-caused fires on lands outside an approved WFU zone might affect the rate of burning within the approved zone. We also used estimates of probability of burning to evaluate selected risks and opportunities from WFU fires.

Evaluation of FMPs

To assess the feasibility of WFU strategies as outlined in the FMP for restoring natural fire regimes, we evaluated how suppression of lightning-caused fires on lands outside approved WFU zones might affect the rate of burning within these zones. By doing so, we asked: *what is the effect of eliminating the importation of these fires?*. Our main analysis consisted of running BurnPro with two different ignition cases ("natural" and "current FMP", Table 5) and comparing the difference between the two. We compared the area averages for the two cases and also calculated the absolute and relative differences on a pixel-by-pixel basis.

For the "natural" case, we ran BurnPro using all lightning ignitions that have occurred during the ~17-year period of record[1] in the study area. The resulting estimates of probability of burning are a proxy for what might be expected if there was no management intervention of the natural fire regime. There are two important caveats to the idea of using this "natural" case as a proxy for natural fire regime, however. First, it ignores ignitions that would have spread in from outside the study area. This is an edge effect that is more pronounced closer to the study area boundary. Ideally, we would have had a large buffer around each study area but in most cases, our fuels and ignition data only extended a short distance outside the park or wilderness boundary and we were unable to buffer the park or wilderness by very much. A second caveat is that these predictions are based on

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[1] 17-years of ignition data used for all study areas except Sequoia-Kings Canyon NP, where we used 19 years of data

current fuels--fuels that have been influenced by human management such as suppression of naturally ignited fires. As a result, the vegetation composition and structure has been altered to varying and largely unknowable degrees. This would be particularly important if vegetation has changed over time from flammable types to inflammable or "fire-proof" types.

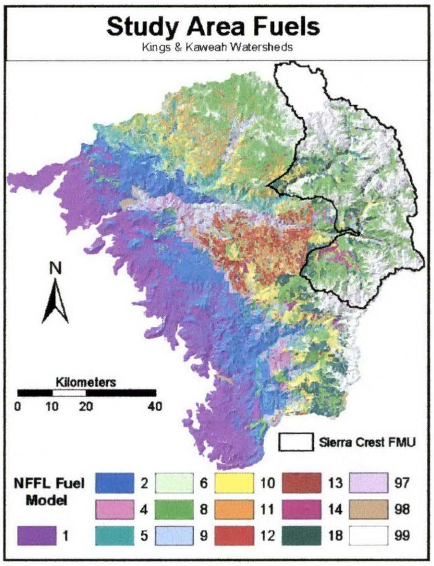
For the "current FMP" case, we ran BurnPro using only the ignitions that fell within an approved WFU zone as delineated in the FMP. These are zones that are typically managed for natural processes applying WFU as the primary tool. These results represent the probability of burning that we might expect under a strict implementation of prescriptions contained in the Fire Management Plan.

We compared the area averages for the "natural" and "current FMP" cases to evaluate how suppression outside the WFU zone affects the rate of burning within the zone (Table 6). In other words, by how much is the probability of burning reduced when we eliminate the importation of fire from outside the area that is being managed for natural processes? When ignitions outside the approved WFU zones are eliminated (i.e., the "current FMP" case) from the BurnPro analysis, the probability of burning is lower than when all ignitions (i.e., the "natural" case) are used (Table 6). This is not surprising: fewer ignitions should result in a lower probability of burning. However, the degree to which these values are reduced varies among the five study areas. For example, this reduction in the WFU zone area average for Sequoia-Kings Canyon is at least six times greater than for the other sites (e.g., a reduction of 0.06 in Sequoia-Kings Canyon compared to a reduction of 0.01 in Gila/Aldo Leopold, Selway-Bitterroot and Yosemite). There a couple of possible reasons for the large difference between the "natural" and "current FMP" cases for Sequoia-Kings Canyon. First, the study area is very large relative to the size of the WFU zone. Therefore, estimates of probability of burning derived for the "natural" case are based on many more ignitions than estimates derived for the "current FMP" case (Table 5). Second, the portion of the study area that is outside the WFU zone for Sequoia-Kings Canyon is at a relatively low elevation with a relatively long fire season (Figure 3). Furthermore, this portion of the study area contains considerable amounts of fast spreading fuels, such as NFFL fuel models 1, 2, and 5 (Figure 7). With a long fire season and fast spreading fuels, the area outside the WFU zone potentially exports a lot of fire to the higher elevation WFU zone.

Table 6. Probability of burning for the two cases used to evaluate FMPs

	Averaged over entire study area		Averaged over WFU zone	
Study Area	**Case 1 ("natural")**	**Case 2 ("current FMP")**	**Case 1 ("natural")**	**Case 2 ("current FMP")**
Gila/Aldo Leopold	0.550	0.510	0.600	0.590
Great Smoky Mtns NP	0.024	0.022	0.023	0.021
Selway-Bitterroot*	0.250	0.150	0.260	0.250
Sequoia-Kings Cyn NP	0.440	0.310	0.230	0.170
Yosemite NP	0.300	0.290	0.260	0.250

Figure 7. NFFL fuels models for Sequoia-Kings Canyon study area.

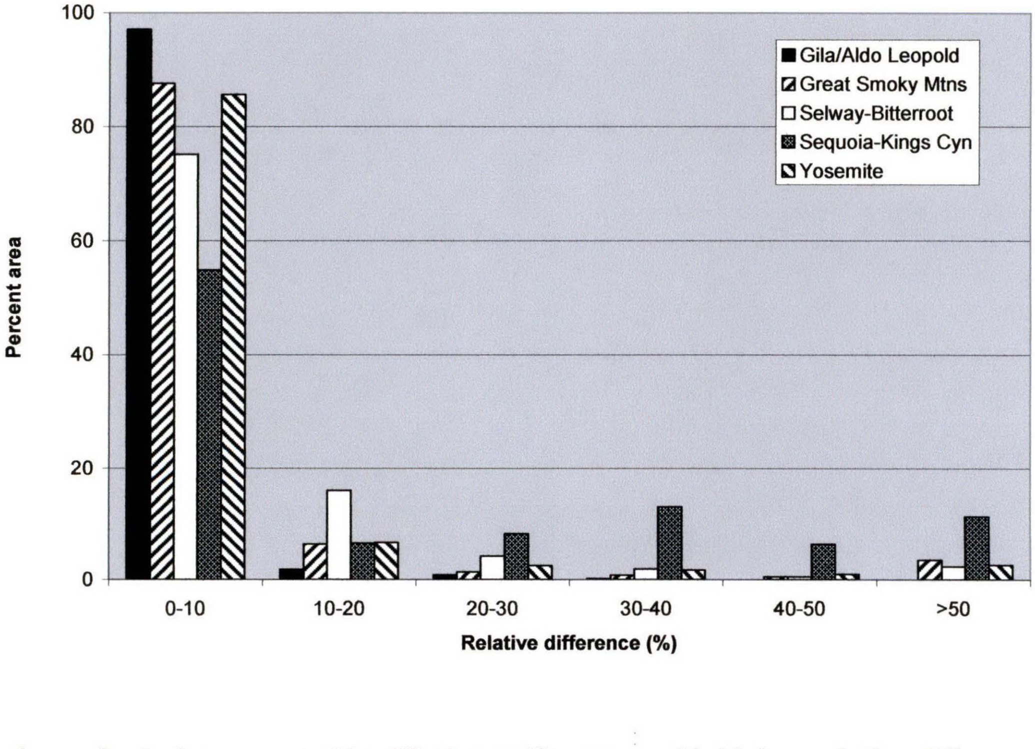


We also found that the degree to which probability of burning differs between the two cases varies greatly *within* a study area. On a pixel-by-pixel basis, we calculated the absolute and relative differences between the two ignition cases. The absolute difference was obtained by simply subtracting -- pixel by pixel -- one probability map from the other. While this is a simple and intuitive analysis, it can be somewhat misleading because the difference between two large values is perceived as the difference between two small values. For example, reducing the probability of burning by 0.10 from 0.50 to 0.40 does not represent the same degree of change as reducing the probability by 0.10 from 0.15 to 0.05. Therefore, we calculated the *relative difference* between the "natural" and "current

FMP" cases as the percentage that the probability differs between the two cases. For example, if the value for a pixel in case 1 is 0.06, and if the value for that same pixel in case 2 is 0.03, the relative difference is 50%. If the values are 0.06 and 0.04, the relative difference is 33%.

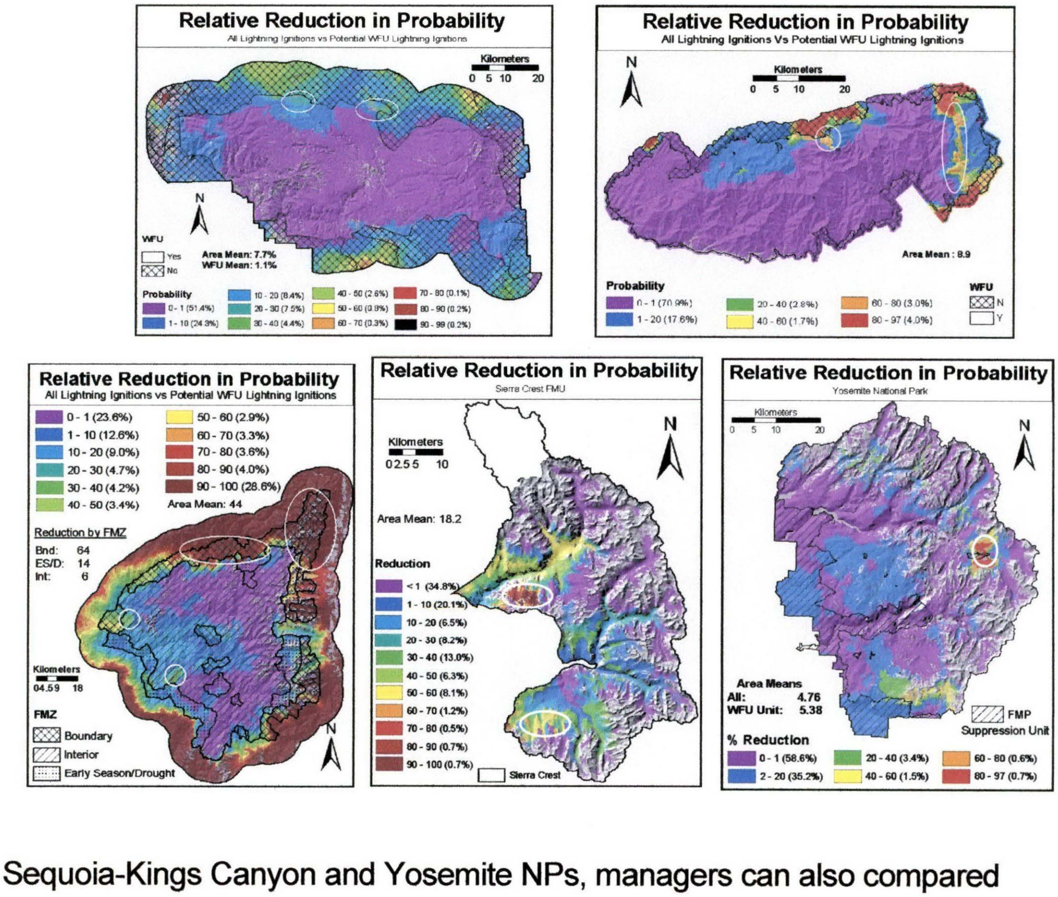
In general, the relative difference was low for the majority of area within the WFU zones. For example, the relative difference between the "natural" and "current FMP" cases was 10 percent or less for the majority of each of the WFU zones (Figure 8). For the Gila/Aldo Leopold, we found the relative difference between the two cases to be 10 percent or less for 97% of the WFU zone. This indicates that the impact of eliminating ignitions outside the WFU zone in the Gila/Aldo Leopold is minor. The relative differences for the WFU zone in Sequoia-Kings Canyon were considerably higher—for 10 percent of the WFU zone we found a relative difference of more than 50% (Figure 8).

Figure 8. Effect of eliminating importation of fires on the probability of burning in WFU zones as illustrated by relative difference between two ignition cases.



In each study area, we identified specific areas with higher relative difference between the two cases. These are areas where the impact of eliminating importation is relatively large, and where it might be more difficult to restore fire to a natural frequency due to management objectives of adjacent lands (Figure 9). In these areas opportunities for WFU should be maximized whenever possible and in some cases periodic prescribed burning over the long term may be warranted. In Yosemite, the effect of eliminating ignitions within a small area around Tuolumne Meadows in the east central part of the park is visible as an hourglass shape of red and orange which extends beyond the boundaries of a relatively small (~400 ha) suppression zone (Figure 9). Although there are numerous other small suppression zones in Yosemite, none of them are quite as large as the Tuolumne Meadows zone and so eliminating ignitions in those smaller areas for the "current FMP" case does not significantly affect the probability of burning in surrounding areas.

Figure 9. Relative difference in probability of burning between the two ignition cases for the Gila/Aldo Leopold (top left), Great Smoky Mountains (top right), Selway-Bitterroot (bottom left), Sequoia-Kings Canyon (bottom center), and Yosemite (bottom right) study areas.


Relative Reduction in Probability
All Lightning Ignitions vs Potential WFU Lightning Ignitions
Kilometers
0 5 10 20
N
WFU
Yes
No
Area Mean: 7.7%
WFU Mean: 1.1%
Probability
0 - 1 (51.4%)
1 - 10 (24.3%)
10 - 20 (8.4%)
20 - 30 (7.5%)
30 - 40 (4.4%)
40 - 50 (2.6%)
50 - 60 (0.8%)
60 - 70 (0.3%)
70 - 80 (0.1%)
80 - 90 (0.2%)
90 - 99 (0.2%)
Relative Reduction in Probability
All Lightning Ignitions Vs Potential WFU Lightning Ignitions
N
Kilometers
0 5 10 20
Area Mean : 8.9
Probability
0 - 1 (70.9%)
1 - 20 (17.6%)
20 - 40 (2.8%)
40 - 60 (1.7%)
60 - 80 (3.0%)
80 - 97 (4.0%)
WFU
N
Y
Relative Reduction in Probability
All Lightning Ignitions vs Potential WFU Lightning Ignitions
0 - 1 (23.6%)
1 - 10 (12.6%)
10 - 20 (9.0%)
20 - 30 (4.7%)
30 - 40 (4.2%)
40 - 50 (3.4%)
50 - 60 (2.9%)
60 - 70 (3.3%)
70 - 80 (3.6%)
80 - 90 (4.0%)
90 - 100 (28.6%)
Area Mean: 44
Reduction by FMZ
Bnd: 64
ES/D: 14
Int: 6
Kilometers
04.59 18
FMZ
Boundary
Interior
Early Season/Drought
N
Relative Reduction in Probability
Sierra Crest FMU
Kilometers
0255 10
N
Area Mean: 18.2
Reduction
<1 (34.8%)
1 - 10 (20.1%)
10 - 20 (6.5%)
20 - 30 (8.2%)
30 - 40 (13.0%)
40 - 50 (6.3%)
50 - 60 (8.1%)
60 - 70 (1.2%)
70 - 80 (0.5%)
80 - 90 (0.7%)
90 - 100 (0.7%)
Sierra Crest
Relative Reduction in Probability
Yosemite National Park
Kilometers
0 5 10 20
N
Area Means
All: 4.76
WFU Unit: 5.38
FMP Suppression Unit
% Reduction
0 - 1 (58.6%)
2 - 20 (35.2%)
20 - 40 (3.4%)
40 - 60 (1.5%)
60 - 80 (0.6%)
80 - 97 (0.7%)

In Sequoia-Kings Canyon and Yosemite NPs, managers can also compared these places where challenges might exist with analyses of Fire Return Interval Departure (FRID). Both parks currently use estimates of FRID to prioritize fuel management activities and to track their progress (Caprio et al. 1997, Keifer et al.

2000, Caprio and Graber 2000, van Wagtendonk et al. 2002). FRID is an estimate of the number of fire cycles an area has missed, and provides a coarse measure of deviation from natural conditions. Areas with high FRID values are defined as highly compromised by past suppression and in greatest need of fuel treatment. Therefore, managers may be interested in areas where both FRID and the relative difference between the two ignition cases are high. In such areas, the deviation of natural conditions indicated by the high FRID could very well be due to the past suppression of fires on adjacent lands that consequently eliminated the importation of fires.

These results provide useful feedback on current FMPs and WFU strategies and can help managers evaluate where the current FMP is likely to meet their expectations or where it might fall short. For example, are the potential WFU ignitions located in the WFU zone likely to burn the amount of area or burn with the frequency that managers expected they would? In a couple of the study areas, management staff asked us to modify the "current FMP" case to evaluate the effect of a potential revision to the FMP revision. Other times, staff asked us to modify the "natural" or "current FMP" cases to better account for realities that are not captured in the FMP.

Identifying Risks and Opportunities

We used our estimates of probability of burning to examine some of the risks and opportunities WFU may pose.

First, maps of probability of burning were overlaid with socio-economic or ecological values to identify where risks from fire are greatest. These areas might be then identified as priorities for fuel treatments or prevention planning. For example, for the Gila/Aldo Leopold Wilderness, we overlaid our estimate of probability of burning with information on Mexican spotted owl habitat and wildland urban interface (WUI) to assess the risk of WFU to both Mexican spotted owl and human life and property (Figure 10). For Great Smoky Mountains NP, we overlaid the probability of burning with the location of historic cemeteries, an important cultural resource that is potentially threatened by fire (Figure 11).

Figure 10. Analysis of risk from WFU to Mexican spotted owl habitat and wildland urban interface for the Gila/Aldo Leopold Wilderness.

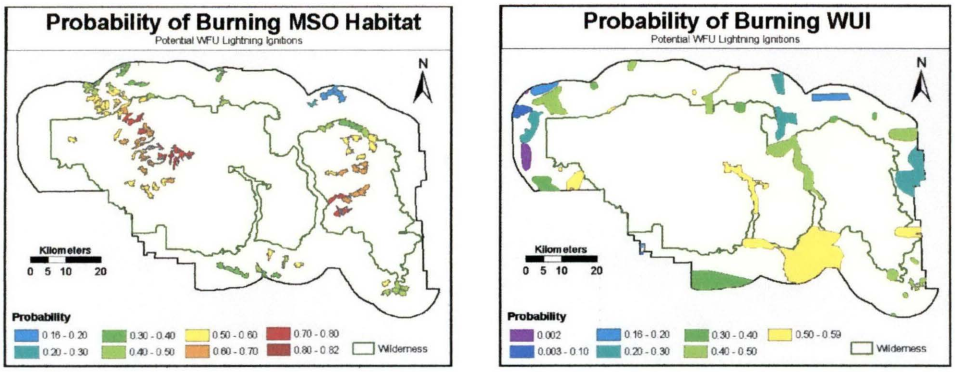
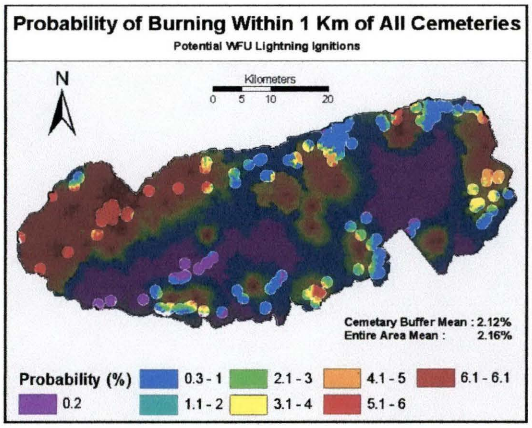

Probability of Burning MSO Habitat
Potential WFU Lightning Ignitions
N
Kilometers
0 5 10 20
Probability
0.16 - 0.20
0.20 - 0.30
0.30 - 0.40
0.40 - 0.50
0.50 - 0.60
0.60 - 0.70
0.70 - 0.80
0.80 - 0.82
Wilderness
Probability of Burning WUI
Potential WFU Lightning Ignitions
N
Kilometers
0 5 10 20
Probability
0.002
0.003 - 0.10
0.16 - 0.20
0.20 - 0.30
0.30 - 0.40
0.40 - 0.50
0.50 - 0.59
Wilderness

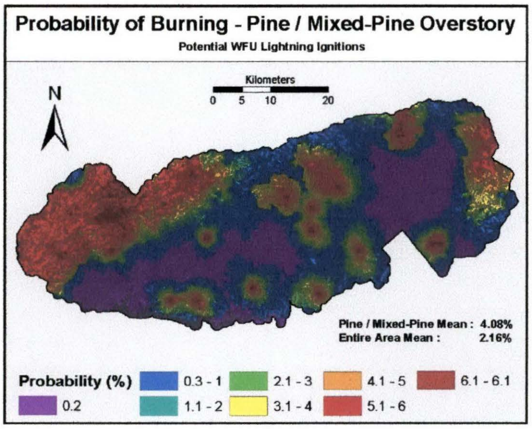
Figure 11. Analysis of risk from WFU to cemeteries in Great Smoky Mountains National Park.


Probability of Burning Within 1 Km of All Cemeteries
Potential WFU Lightning Ignitions
N
Kilometers
0 5 10 20
Cemetary Buffer Mean : 2.12%
Entire Area Mean : 2.16%
Probability (%)
0.2
0.3 - 1
1.1 - 2
2.1 - 3
3.1 - 4
4.1 - 5
5.1 - 6
6.1 - 6.1

The resulting map of probability of burning can also be viewed in terms of opportunities for WFU. WFU opportunities may be fairly common or frequent in areas with high probability of burning, whereas WFU opportunities are rare in areas with low probability of burning. This information can help inform the go/no-go decision. If a suppression decision has to be made in an area of high probability of burning due to external factors (e.g., national preparedness level, air quality concerns, etc.), managers can expect that another opportunity for WFU is likely to occur again relatively soon. On the other hand, in areas with low probability of burning, managers may want to more carefully scrutinize suppression decisions because of the rarity of such opportunities for WFU.

WFU also provides specific benefits to the resource and we used our estimates of probability of burning to identify some of these. For example, in Great Smoky Mountains NP there are estimated to be at least a dozen species of native plants and animals that benefit from fire. One of these species is Table Mountain pine, which has serotinous cones that open in response to fire, allowing the dispersion of their seeds onto the fire-cleared ground. Table Mountain pine has experience a decline in population over the past 100 years. For Great Smoky Mountains NP, we examined the opportunities for WFU to *benefit* the resource by overlaying the probability of burning with maps of fire-dependent yellow pine species as a whole (of which Table Mountain pine is an example) (Figure 12).

Figure 12. Analysis of benefits to fire-dependent pine species for Great Smoky Mountains National Park.

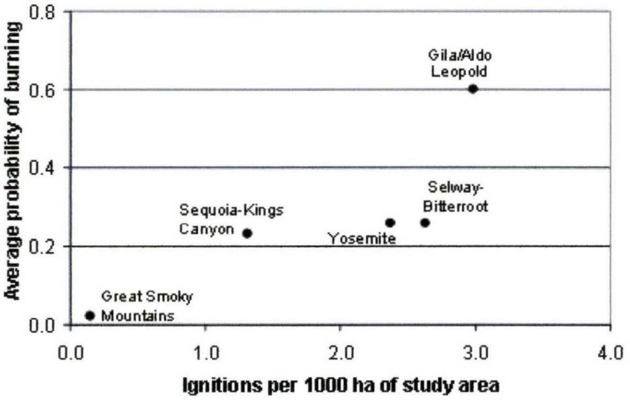

Probability of Burning - Pine / Mixed-Pine Overstory
Potential WFU Lightning Ignitions
N
Kilometers
0 5 10 20
Pine / Mixed-Pine Mean : 4.08%
Entire Area Mean : 2.16%
Probability (%)
0.2
0.3 - 1
1.1 - 2
2.1 - 3
3.1 - 4
4.1 - 5
5.1 - 6
6.1 - 6.1

Management staff at all of the study areas were interested in seeing the probability of burning derived using *human-caused and* lightning-caused ignitions to help improve their risk assessments. In addition, the Gila National Forest requested additional analyses for the entire National Forest, an area of 1.5 Mha.

Synthesis

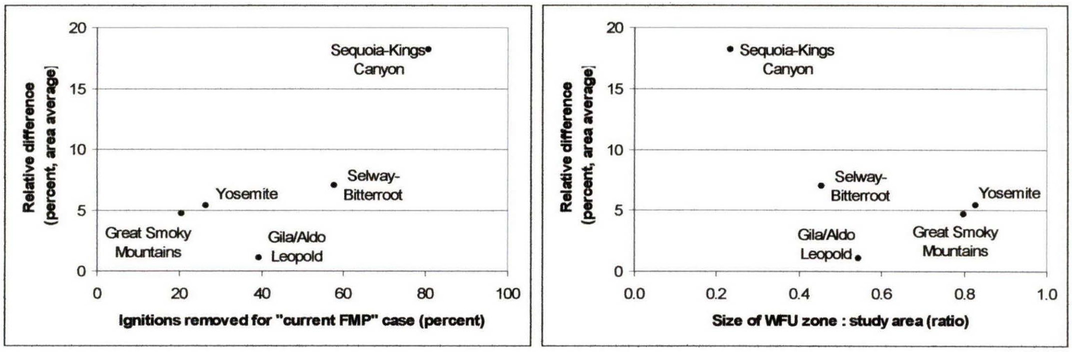
It was difficult to make direct comparisons among the five study areas because the the extent and definition of study area boundaries varied according to the data we had available. For example, the buffer areas around Selway-Bitterroot and Gila were much more generous (~10 km) than for Yosemite or Great Smoky Mountains NP, which had virtually no buffer. It is instructive, however, to examine the five study areas as a group. Figure 13 illustrates the differences among study areas in ignition densities and average annual probability of burning.

Figure 13. Comparison of study areas by probability of burning (averaged over the WFU zone) and density of ignitions for the study area ("natural" case).



Summer-monsoon and summer-moist. Summer precipitation influences the probability of burning for two of our sites: Gila/Aldo Leopold Wilderness and Great Smoky Mountains National Park. Gila/Aldo Leopold typically experiences a summer monsoon in late July that serves to limit the probability of burning. Frequent summer precipitation in Great Smoky Mountains National Park similarly limits the probability of burning at that site. Despite this similarity, the fire management and restoration challenges at these two sites are extremely different from one another. In terms of absolute probability of burning (Table 6, Figure 13), these two sites represent two different ends of the spectrum. Gila/Aldo Leopold has the highest density of ignitions, and therefore many opportunities for WFU and the highest probability of burning. Eliminating ignitions outside the WFU zone for the Gila/Aldo Leopold does not appear to have much of an effect on the average probability of burning within the WFU zone (Figure 14). Therefore, our analyses suggest that Gila/Aldo Leopold has a very good chance of maintaining natural fire frequencies with WFU, although there are resource values potentially threatened by fire that need to considered. Great Smoky Mountains, on the other hand, has the lowest density of ignitions, and therefore few opportunities for WFU and the lowest probabilities of burning (Figure 13). Although BurnPro's estimates should be interpreted only as relative probabilities, when we compared the absolute values for our study areas, it was apparent that Great Smoky Mountains NP has an exceptionally low chance of burning. For large portions of the interior of this park, BurnPro output suggests that there is little or no chance of burning from a lightning ignition. In comparison to Gila/Aldo Leopold, Great Smoky Mountains has virtually no opportunity to restore fire regimes through WFU and will likely continue to lose fire dependent species as a result. As such, an aggressive prescribed burning program is probably the park's best approach for achieving conservation objectives.

Figure 14. Effect of eliminating ignitions from outside the WFU zone, approximated by relative difference between the "natural" and "current FMP" cases. Relative difference is shown as a function of the number of ignitions removed from the analysis for the "current FMP" case and as a function of the size of the WFU zone relative to the size of the study area.



Summer-dry. The three remaining sites are in the summer-dry category and in these study areas, the elevational variation in the length of fire season is more important than summer precipitation for estimating probability of burning. These three sites have ignition densities and values of probability of burning that are intermediate between the Gila/Aldo Leopold and Great Smoky Mountains NP (Figure 13). Figure 14 illustrates the relative difference, averaged over the WFU zone for each study area. The relative difference between the "natural" and "current FMP" cases is one way to compare the impact of eliminating importation of fires. Because Sequoia-Kings Canyon and Yosemite NP have similar climates, vegetation, and fire regimes, we might expect them to be comparable. However, our analysis indicates that Sequoia-Kings Canyon has the greatest relative difference (Figure 14), suggesting that the importation of fires is more important there. This also suggests that suppression outside the WFU zone will limit the ability to restore natural fire regimes to the WFU zone more so in Sequoia-Kings Canyon than in Yosemite.

Model Development

We discovered problems in the original implementation of the model BurnPro and spent several months correcting these problems. For example, we discovered logical inconsistencies in the model regarding the assumed direction of fire spread and the whether the rate of spread referred to heading, flanking, or backing fires. We also discovered a logical fallacy in the assumed timing of the fire season for areas on the landscape with very short fire seasons (e.g., high elevations with a fire season <30 days). In addition to correcting these logical problems, we reprogrammed the model to make it more widely applicable and easier to use in multiple study areas. Another important modification we made was adding second sub-probability to account for fire-stopping precipitation events that may occur before the actual end of the fire season. Prior to this modification, the probability of burning was calculated solely from what is now the first sub probability—the probability that fire would reach a pixel before the end of the fire season.

Although these improvements were not anticipated in our original proposal, they provided more meaningful and defensible analyses for fire management planning. Furthermore, the development, testing, and use of BurnPro that was done within the scope of this project is an important foundation for what may become a widely distributed analysis tool.

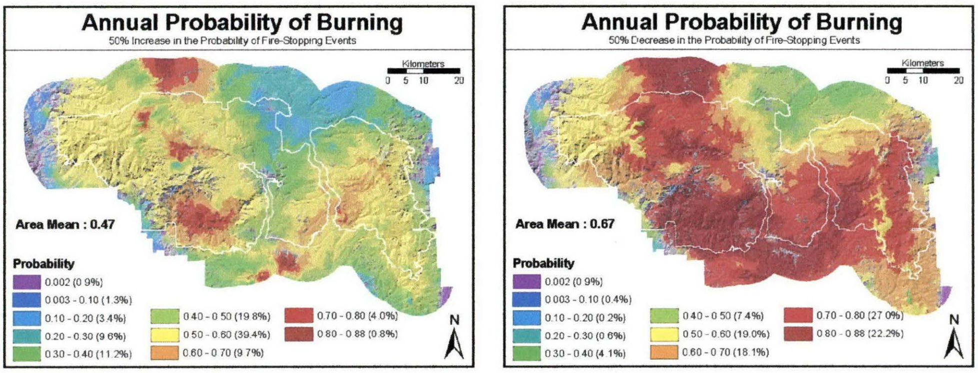
Sensitivity Analyses

Any model will have a degree of sensitivity to each of the variables within it. It is important to understand the model's sensitivity, particularly to those variables we are most uncertain about or for which we lack reliable data. Through an analysis of this sensitivity, we can prioritize our data needs and better understand the uncertainty of the model output. We conducted a sensitivity analysis of three important variables in BurnPro: frequency of fire-stopping precipitation events (which is used to compute *PStop*); length of fire season (used to compute *PEnd*); and rate-of-spread (which is used to compute CST for both *PEnd* and *PStop*).

Frequency of fire-stopping events

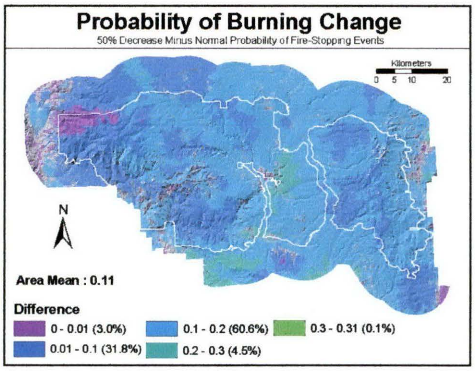
Increasing the frequency of fire-stopping events should decrease the probability of burning. For the Gila/Aldo Leopold Wilderness these events are defined as 0.5 inches of rain occurring in 5 days. To test the sensitivity of BurnPro output to this variable, we increased and decreased the monthly frequency of fire-stopping events by 50% and compared the resulting probability of burning (Figure 15) with the "normal" case.

Figure 15. Probability of burning estimates for the Gila/Aldo Leopold Wilderness with 50% increase and 50% decrease in the monthly frequency of fire-stopping events.


Annual Probability of Burning
50% Increase in the Probability of Fire-Stopping Events
Kilometers
0 5 10 20
Area Mean : 0.47
Probability
0.002 (0.9%)
0.003 - 0.10 (1.3%)
0.10 - 0.20 (3.4%)
0.20 - 0.30 (9.6%)
0.30 - 0.40 (11.2%)
0.40 - 0.50 (19.8%)
0.50 - 0.60 (39.4%)
0.60 - 0.70 (9.7%)
0.70 - 0.80 (4.0%)
0.80 - 0.88 (0.8%)
N
Annual Probability of Burning
50% Decrease in the Probability of Fire-Stopping Events
Kilometers
0 5 10 20
Area Mean : 0.67
Probability
0.002 (0.9%)
0.003 - 0.10 (0.4%)
0.10 - 0.20 (0.2%)
0.20 - 0.30 (0.6%)
0.30 - 0.40 (4.1%)
0.40 - 0.50 (7.4%)
0.50 - 0.60 (19.0%)
0.60 - 0.70 (18.1%)
0.70 - 0.80 (27.0%)
0.80 - 0.88 (22.2%)
N

Changing the frequency of fire-stopping events does indeed affect the probability of burning and the difference is noticeable (Figure 15). Less frequent fire-stopping events result in higher estimates of probability of burning. When we examined the resulting from reducing the fire-stopping events by 50%, we found that probability estimates were increased by at least 0.10 for about 65% of the land area (Figure 16). Furthermore, the degree of this difference varies spatially within the landscape, indicating that the probability of burning for some places on the landscape is more sensitive than others when the frequency of heavy rains changes. These differences could indicate places on the landscape where fire frequencies may be more sensitive to interannual variability in precipitation.

Figure 16. Difference in probability of burning between the baseline case and a 50% decrease in the frequency of fire-stopping events for the Gila/Aldo Leopold Wilderness.


Probability of Burning Change
50% Decrease Minus Normal Probability of Fire-Stopping Events
Kilometers
0 5 10 20
N
Area Mean : 0.11
Difference
0 - 0.01 (3.0%)
0.01 - 0.1 (31.8%)
0.1 - 0.2 (60.6%)
0.2 - 0.3 (4.5%)
0.3 - 0.31 (0.1%)

Length of fire season

Increasing the length of the fire season should increase the probability of burning. To test the sensitivity of BurnPro estimates to this variable, we increased the length of the fire season by shifting the fire season for Yosemite National Park uphill by 500m (Figure 17). This shift approximately doubles the amount of area that has a 4-month or longer fire season (Figure 18).

Figure 17. Original length of fire season and length of fire season shifted uphill by 500 m for Yosemite National Park.

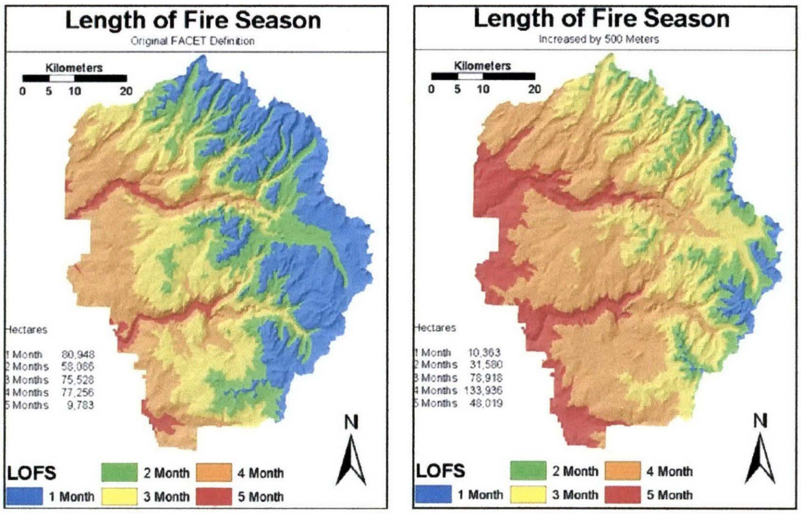
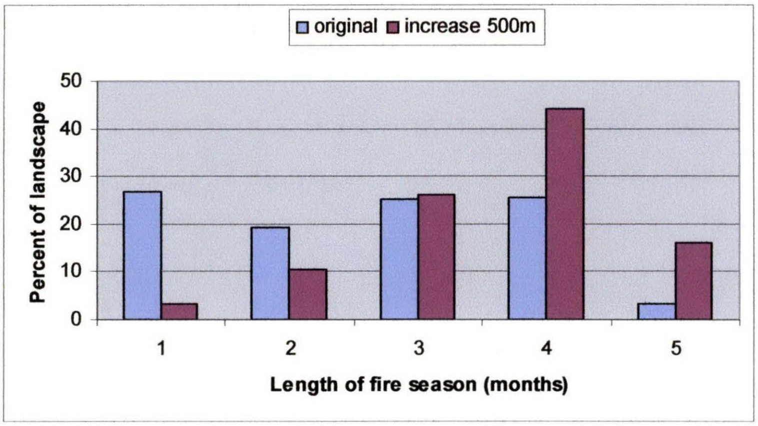

Length of Fire Season
Original FACET Definition
Kilometers
0 5 10 20
Hectares
1 Month 80,948
2 Months 58,086
3 Months 75,528
4 Months 77,256
5 Months 9,783
N
LOFS
1 Month
2 Month
3 Month
4 Month
5 Month
Length of Fire Season
Increased by 500 Meters
Kilometers
0 5 10 20
Hectares
1 Month 10,363
2 Months 31,580
3 Months 78,918
4 Months 133,936
5 Months 48,019
N
LOFS
1 Month
2 Month
3 Month
4 Month
5 Month

Figure 18. Distribution of original length of fire season and fire season shifted uphill by 500 m for Yosemite National Park.



The effect of a longer fire season on annual probability of burning isn't very dramatic at a landscape scale (Figures 19 and 20), suggesting that BurnPro isn't very sensitive to length of fire season. Although this variable has a fairly high degree of uncertainty, results from this sensitivity analysis suggest that improving these data should not be a high research priority.

Figure 19. Probability of burning estimates for Yosemite NP derived using the original definition of length of fire season as a function of elevation and using an increase in fire season equivalent to an uphill shift of 500m.

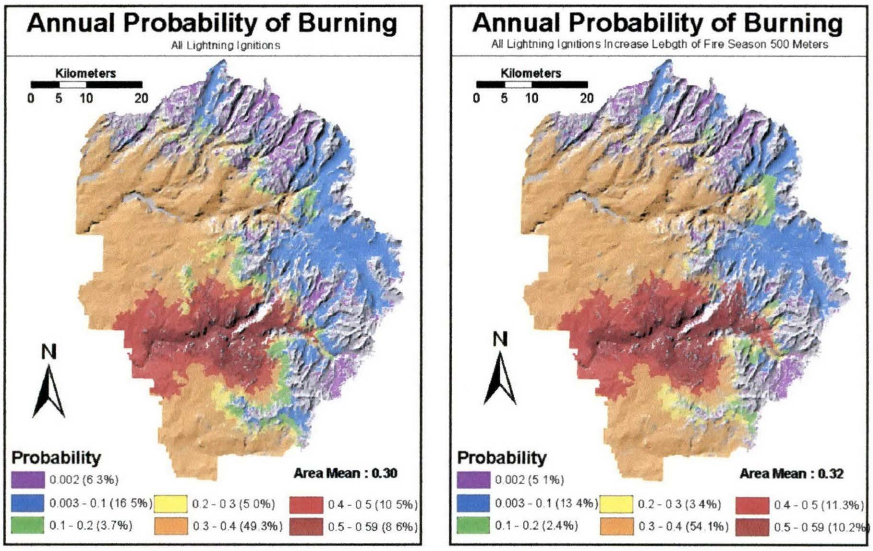
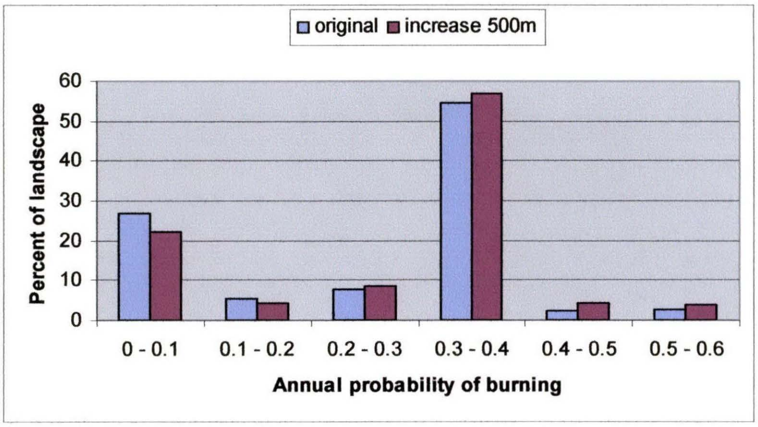
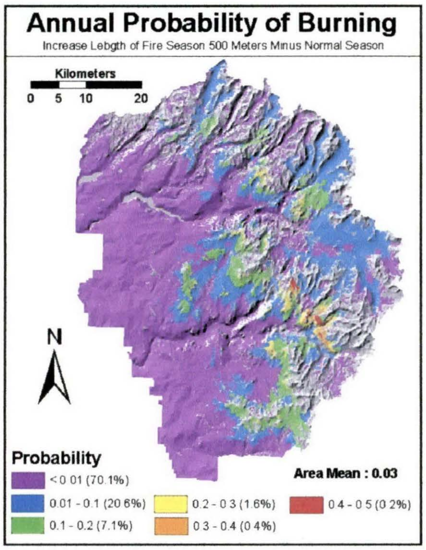

Annual Probability of Burning
All Lightning Ignitions
Kilometers
0 5 10 20
N
Probability
0.002 (6.3%)
0.003 - 0.1 (16.5%)
0.1 - 0.2 (3.7%)
0.2 - 0.3 (5.0%)
0.3 - 0.4 (49.3%)
0.4 - 0.5 (10.5%)
0.5 - 0.59 (8.6%)
Area Mean : 0.30
Annual Probability of Burning
All Lightning Ignitions Increase Lebgth of Fire Season 500 Meters
Kilometers
0 5 10 20
N
Probability
0.002 (5.1%)
0.003 - 0.1 (13.4%)
0.1 - 0.2 (2.4%)
0.2 - 0.3 (3.4%)
0.3 - 0.4 (54.1%)
0.4 - 0.5 (11.3%)
0.5 - 0.59 (10.2%)
Area Mean : 0.32

Figure 20. Distribution of probability of burning estimates derived using the original definition of length of fire season as a function of elevation and using an increase in fire season equivalent to an uphill shift of 500m.



However, direct point-to-point comparison reveals that certain places on the landscape are much more sensitive to this variable than others (Figure 21). The changing sensitivity to this variable across the landscape demonstrates the importance of the spatial configuration of fuels, topography, and ignitions and the need for approaches that explicitly account for this spatial context or topology.

Figure 21. Difference in probability of burning estimates derived using the original definition of length of fire season as a function of elevation and using an increase in fire season equivalent to an uphill shift of 500m.

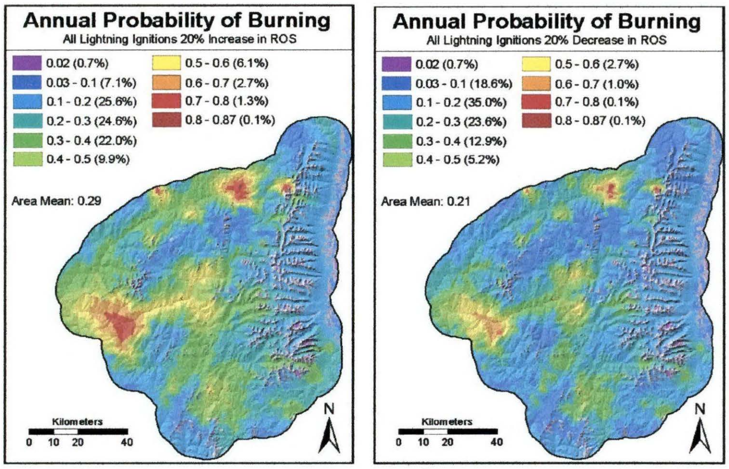

Annual Probability of Burning
Increase Lebgth of Fire Season 500 Meters Minus Normal Season
Kilometers
0 5 10 20
N
Probability
<0.01 (70.1%)
0.01 - 0.1 (20.6%)
0.1 - 0.2 (7.1%)
0.2 - 0.3 (1.6%)
0.3 - 0.4 (0.4%)
0.4 - 0.5 (0.2%)
Area Mean : 0.03

The results of this sensitivity analysis may have important implications for fire management under future climate change. Currently, most *lightning strikes* in Yosemite occur at higher elevations, but most *ignitions* occur at lower elevations because that is where fuel conditions are suitable for burning for long periods of time (van Wagtendonk 1993). If lightning patterns continue to remain the same and if conditions at higher elevations become dry enough to support fire for longer periods of time during the season, the park could experience a substantial increase in future rates of burning. However, since climate change also causes changes in vegetation and fuels, additional research on the complex interactions among climate, fuels and fire is needed to fully flesh out the management implications (Miller and Urban 1999).

Rate of spread

Finally, increasing the rate of spread should increase our estimates of the probability of burning. To test the sensitivity of BurnPro's estimates to this variable, we ran BurnPro for the Selway-Bitterroot Wilderness using rate-of-spread values that we decreased by 20% and again using rate-of-spread values that we increased by 20% (Figure 22).

Figure 22. Probability of burning for the Selway-Bitteroot Wilderness derived using 20% faster and 20% slower rates-of-spread.


Annual Probability of Burning
All Lightning Ignitions 20% Increase in ROS
0.02 (0.7%)
0.03 - 0.1 (7.1%)
0.1 - 0.2 (25.6%)
0.2 - 0.3 (24.6%)
0.3 - 0.4 (22.0%)
0.4 - 0.5 (9.9%)
0.5 - 0.6 (6.1%)
0.6 - 0.7 (2.7%)
0.7 - 0.8 (1.3%)
0.8 - 0.87 (0.1%)
Area Mean: 0.29
Kilometers
0 10 20 40
N
Annual Probability of Burning
All Lightning Ignitions 20% Decrease in ROS
0.02 (0.7%)
0.03 - 0.1 (18.6%)
0.1 - 0.2 (35.0%)
0.2 - 0.3 (23.6%)
0.3 - 0.4 (12.9%)
0.4 - 0.5 (5.2%)
0.5 - 0.6 (2.7%)
0.6 - 0.7 (1.0%)
0.7 - 0.8 (0.1%)
0.8 - 0.87 (0.1%)
Area Mean: 0.21
Kilometers
0 10 20 40
N

The values for rate-of-spread that we use as input to BurnPro are computed using another model (FlamMap) and therefore come complete with their own degree of uncertainty. Through this sensitivity analysis, we can begin to understand the effect that uncertainties in other models might have on our estimates of probability of burning. The level of error in FlamMap's rate-of-spread predictions probably varies depending on fuel types. To improve future analyses of sensitivity, it would be advantageous to consult with the developers of FlamMap to design scenarios that consider varying degrees of error for each fuel type.

Chapter 5 Conclusions

Fire is a contagious process that responds to a multivariate landscape and is one that does not obey administrative boundaries. As such, effective fire management planning needs to account for the spatial context and configuration of landscape variables, and it needs to do so across administrative boundaries. In particular, effective planning needs to consider the effects that fire management activities on one side of a boundary can have on the other side of the boundary. Prior to this project, we know of no methods that could be used to evaluate such effects while accounting for a landscape's unique spatial configuration of fuels, topography and ignitions.

We developed methods for evaluating effects that fire suppression on one side of an administrative boundary might have on the other side of that boundary. We used these methods to evaluate how suppression of lightning-caused ignitions that occur *outside* WFU zones might affect our ability to achieve the restoration of fire *inside* the WFU zones. Specifically, we examined how eliminating the importation of fires that start on adjacent lands affects the predicted rate of burning for the WFU zone. Furthermore, we developed and demonstrated our approach using multiple study areas that have very different precipitation regimes. As such, the approach we developed is a robust one that can integrate information on summer precipitation patterns as well as patterns of season length over elevation.

Cross-boundary fire management planning requires cross-boundary information and data. We buffered around the boundaries of our study areas as much as possible, but in only one study area (Sequoia-Kings Canyon National Park) did we have a data set available to us that provided a true interagency perspective. This data set was the result of a previous project funded by the JFSP that created the Southern Sierra Geographic Information Cooperative (JFSP #99-1-3-04). This effort developed data that extend across administrative boundaries, thus allowing analyses and planning to also extend across boundaries.

Although we were unable to directly compare the estimates of probability of burning to historical fire frequencies (our original intent), we did identify specific places in each study area where restoration of natural fire frequency may be difficult because of the important influence of immigration of fires. This knowledge can help inform the go/no-go decision and we suggest that whenever possible, these areas receive the highest priority for WFU. If WFU is not possible, these are places where management-ignited prescribed fires might be warranted.

Originally, we expected to use the information generated to delineate fire management zones in fire management plans (FMPs). Although we believe this is a valid use of our analyses, the study areas we selected already had established FMPs and did not have a need for this application. Therefore, we used our analyses to evaluate these existing FMPs and to identify where the greatest challenges to meeting restoration objectives can be expected.

Developing a prediction tool that accounts for the spatial configuration of multiple variables on a landscape and the contagion of fire is not a trivial exercise. While we have developed one set of methods, we are certain these methods can be improved upon. We expect to collaborate with other researchers to compare and contrast other approaches for modeling the probability of burning. We expect that these efforts will not only require an understanding of what makes fires *start* and *spread* (i.e., the focus of much fire research to date), but also an understanding of how long fires can be expected to spread and what makes them *stop.* Therefore, we will encourage work that adapts the fundamental concepts in the incident support tool RERAP (Wiitala and Carlton 1994, FRAMES 2003) to longer time scales and multiple incidents.

Prospectus

The development, testing, and use of BurnPro that was done within the scope of this project is an important foundation for what we believe could become a widely distributed analysis tool. In particular, our experimental release of BurnPro for use on the Cloud Peak Wilderness and feedback from our lecture at the Technical Fire Management course have encouraged us to pursue the idea of a stand-alone tool. We have already identified several modeling issues that we need to address and resolve in BurnPro. By leveraging results from this project with continued support from the National Fire Plan, we hope to produce and release a user-friendly version of BurnPro in FY2006 for use by the fire and fuels management community.

Several opportunities for collaboration were generated as a result from this project. For example, BurnPro is being evaluated for use in the Front Range Fuel Treatment Project in Harris Park, Colorado. We have met with research partners (ESRI and the Colorado State Forest Service) and have provided a copy of the current model and preliminary documentation for this purpose. We are currently collaborating on a project proposal to NASA with researchers from the University of Georgia and management staff from Great Smoky Mountains National Park. The project would provide improved linkages between remotely sensed data and fire management decision support tools, including BurnPro. Another pending proposal (to JFSP) from the USDA Forest Service Rocky Mountain Research Station's Boise Aquatics Lab would likely utilize BurnPro in a decision support system for integrating aquatic species needs. We expect to test the individual functions in the BurnPro model and compare their behavior with other approaches, including "Monte Carlo" simulations of FARSITE, the Minimum Travel Time tool, and a model developed by the Canadian Forest Service (BurnP3).

Finally, management staff identified several additional applications for the probability of burning analyses. With the procedures we have provided in the guidebook, we expect they will be able to run the BurnPro model and conduct their own analyses.

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Appendix A Publications

Proceedings Paper

Davis, B., C. Miller. 2004. Modeling Wildfire Probability Using a GIS. In: Proceedings of the ASPRS 2004 Annual Conference, Denver, USA. May 23-28. American Society of Photogrammetry and Remote Sensing (CDROM).

MODELING WILDFIRE PROBABILITY USING A GIS

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To help land managers plan for Wildland Fire Use (WFU), we developed a GIS model, BurnPro, to predict the annual probability of burning for every cell on a raster landscape (Miller, 2003). BurnPro uses topography, historic weather, fuel model data, and historic ignition locations to estimate the likelihood of burning given the speed and direction a fire might spread from any ignition point. The approach in BurnPro follows logic similar to that used in the fire management application tool RERAP (Rare Event Risk Assessment Program), which estimates the likelihood that a fire will threaten a designated geographic location or point of concern before a fire ending event (i.e. precipitation) will occur (FRAMES 2003). Whereas RERAP is used to perform a nonspatial analysis for a single fire incident, BurnPro translates this concept to a spatially explicit landscape for multiple possible fire incidents occurring over time periods ranging from years to decades. The probability that fire will travel through space and time from an ignition source to any point on the landscape depends upon 1) the time required for fire to travel the distance from the ignition to the target, 2) the frequency distribution of fire-stopping weather events (e.g. heavy rains) within the fire season and 3) the time remaining in the fire season.

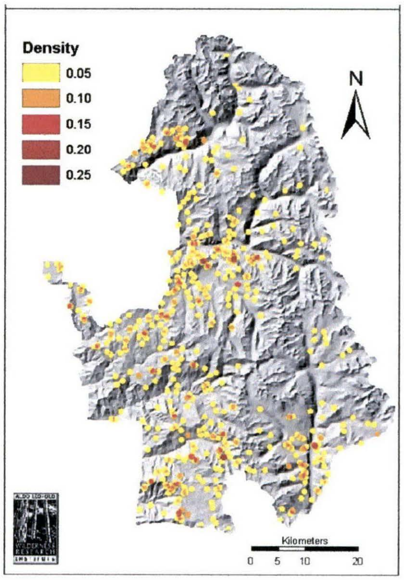

Figure 1. Annual density (km^{-2}) of lightning-caused ignitions in Sequoia-Kings Canyon National Parks, California.

The time required for fire to spread from an ignition point to any other point on the landscape was calculated using the ArcGIS function PATHDISTANCE. This function "calculates, for each cell, the least-accumulative-cost distance over a cost-surface from a source cell or set of source cells" (ESRI 1998).

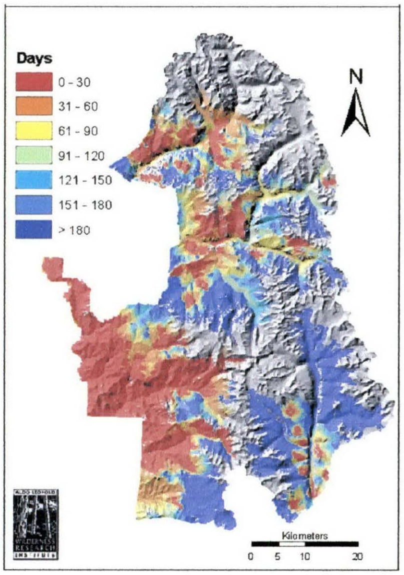

Figure 2. Cumulative spread time under 98th percentile SC fire weather conditions, SW winds, and the lowest density class (0.05 km^{-2}) June ignitions.

In this case the source cells are the ignition locations and the cost-surface is the time required for fire to pass through the cell. Point location data for 20 years of lightning-caused ignitions were separated into 4 months (June, July, August, and September) and then used to derive ignition density grids representing 1, 2, 3, 4, and 5+ ignitions per km^2 per month / 20 years (Figure 1). The resultant density grids were used as the source cells in the PATHDISTANCE function.

To derive the time required for fire to pass through each cell, we used the expected rate of spread under different weather conditions. 20 years of historic weather data were analyzed for 3 weather stations. FireFamilyPlus (Main et al. 1990) was used to compute the Spread Component (SC) index; these were used to define 4 classes (low, moderate, high, and extreme) of fire weather conditions. Expected rate of spread (ROS) was calculated using FlamMap (Fire Sciences Lab 2003) for every combination of the 4 weather classes and 8 separate wind directions. FlamMap computes potential fire behavior for every cell in a raster landscape. Because ROS varies greatly with diurnal variations in temperature and relative humidity we developed average daily ROS grids from multiple FlamMap runs. The inverse of ROS was calculated to determine the time required to pass through each cell. The resultant density grids were used as the cost surface in the PATHDISTANCE function.

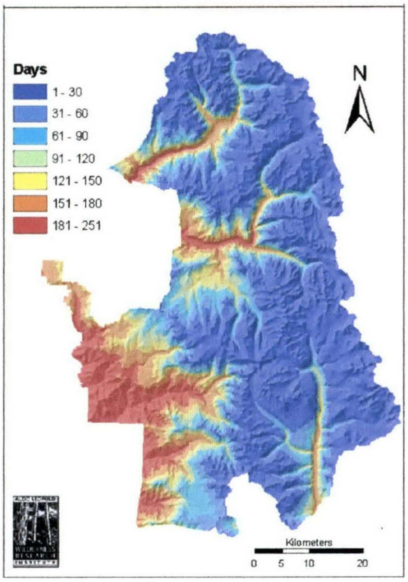

Figure 3. Length of the fire season approximated using a simulation model of soil moisture (Urban et al. 2000).

FlamMap calculates the ROS for the maximum spread direction (heading direction), but fire travels in other directions (i.e. backing or flanking) at lesser rates of spread as well. To account for this fact we used a combination of another FlamMap output, maximum spread direction, and the horizontal factor option in PATHDISTANCE to determine non-maximum spread direction times. The horizontal factor option adjusts the spread-cost, in our case time to cross the cell, for non-maximum directions of travel. The magnitude of the adjustment is largely dependent upon wind speed and slope (Anderson, 1983 and Fons, 1946).

These data were used to calculate least accumulative spread time grids, using PATHDISTANCE, for each unique combination of ignition density class, month, fire-weather class and wind direction (Figure 2). In this example, there were 640 least accumulative spread time grids (5 ignition densities x 4 months x 4 weather classes x 8 wind directions).

FireFamilyPlus (Main et al. 1990) was used to determine the frequency of significant rain events (at least 0.5 inches within 5 days or less; Latham and Rothermel 1993) for each month in the fire season. These frequencies were used to determine the probability that fire will spread to each cell on the landscape before such an event occurs. Subtracting the resultant probability from 1 gives the probability that fires are unhindered by precipitation during the fire season.

Fire season may range from several months at low elevations to perhaps only a few days at the highest elevations. We used a soil moisture model to calculate a drought-day index at 100-m elevation intervals (Urban et al. 2000), and used this index to approximate the length of the fire season across the landscape (Figure 3). The probability that fire will spread to each cell on the landscape before the end of the fire season was calculated for each of the 640 least accumulative spread time grids

These two probability calculations resulted in 1280 probability grids, two for each unique combination of ignition density, month, weather class and wind direction. The two probability grids were then combined into an overall probability of burning grid. This resulted in 640 probability of burning grids that, in turn, were combined using a weighted average approach where the weights were assigned according to the frequency of occurrence (Miller 2003). The result was an average estimate of the annual probability of burning (Figure 4).

The average annual probability of burning is being used in combination with information on values at risk to help managers delineate zones where WFU may be a feasible fire management strategy. Where current conditions allow for WFU, we are evaluating if there are sufficient natural ignitions to restore natural fire frequencies. We are identifying those areas where restoration objectives can be most easily met through the use of natural ignitions; these areas could be given priority for implementing WFU programs. This information is also be used to help identify areas within candidate WFU zones where the number, location, and timing of natural ignitions are inadequate for restoring historic fire regimes. In these areas, the use of prescribed fire, or even accidental human-caused ignitions, is being evaluated in light of restoration objectives. We are currently conducting these analyses for three national parks (Yosemite, Sequoia-Kings Canyon, and Great Smoky Mountains) and two Forest Service wilderness areas (Selway-Bitterroot and Gila-Aldo Leopold).

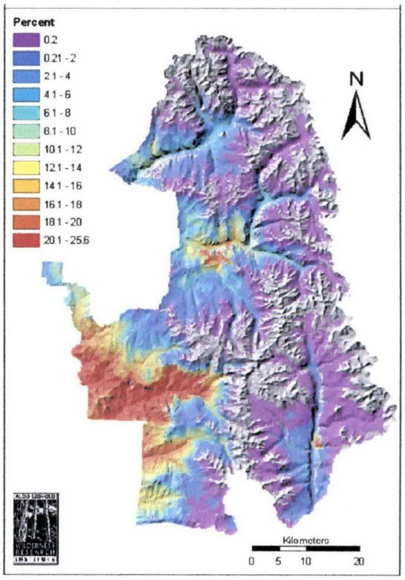

Figure 4. Annual probability of burning for current fuel conditions.

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Research in a Nutshell

The feasibility of wildland fire use for restoring natural fire regimes, Aldo Leopold Wilderness Research Institute, http://leopold.wilderness.net.

RESEARCH IN A NUTSHELL

ALDO LEOPOLD WILDERNESS RESEARCH INSTITUTE
http://leopold.wilderness.net/

THE FEASIBILITY OF WILDLAND FIRE USE FOR RESTORING NATURAL FIRE REGIMES

Keywords: wildland fire use, historical fire regimes, wildland urban interface, prescribed fire, GIS modeling

Background & Management Issues:

Unroaded areas and areas managed as wilderness provide unique opportunities for applying wildland fire use (WFU) as a fuels management strategy to restore fire to fire-dependent ecosystems. Underlying most current fire policies that emphasize WFU is the assumption that natural ignitions are sufficient for restoring or maintaining fire-dependent ecosystems.

In many wilderness areas, current fuel conditions may preclude the use of wildland fire because of excessive risks to either natural resource values within the wilderness or social values in the adjacent wildland urban interface (WUI). Ignitions outside of these areas that otherwise would immigrate into wilderness are usually suppressed, further limiting the amount of natural fire that can occur. Before investing limited time and resources in developing and implementing a fire management plan, wildland fire and fuels managers need information and tools to help them evaluate the feasibility of WFU as a fuel reduction strategy and as a method for the restoration of fire to its historic role.

Project Objectives:

- To develop an approach for assessing the feasibility of WFU for restoring fire to landscapes.
- To identify where WFU opportunities are greatest and improve evaluation of the risk from WFU fires to areas where fire is undesirable.

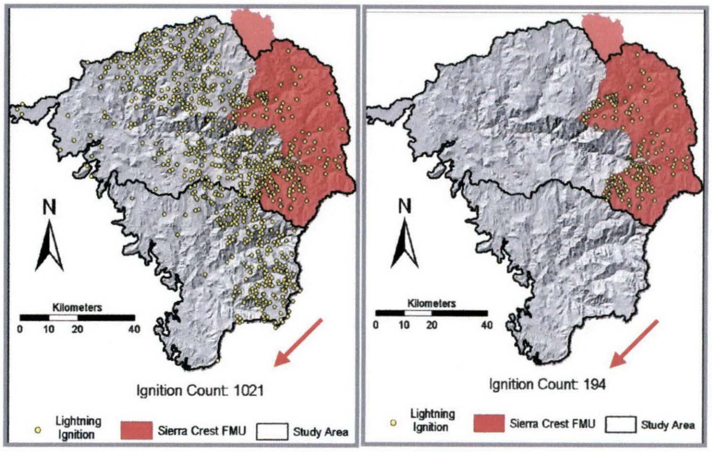
Project Description:

The feasibility of using WFU for restoration of historical fire regimes was assessed in five areas that are designated wilderness or managed primarily as wilderness: the Selway-Bitterroot Wilderness, Gila-Aldo Leopold Wilderness Complex, Yosemite National Park and Sequoia-Kings Canyon National Parks, and Great Smoky Mountains National Park.

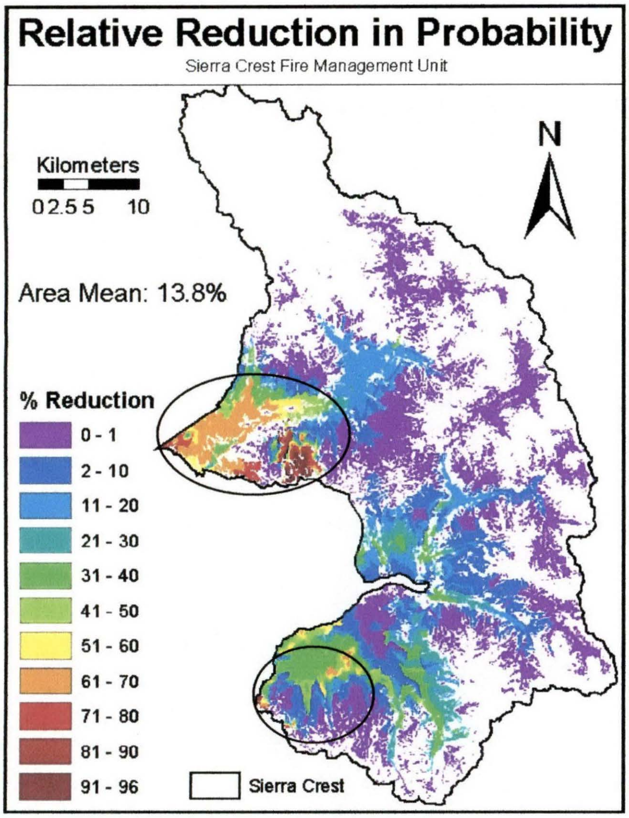
BurnPro:

A GIS model called BurnPro was used to predict the annual probability of burning for every cell on a raster landscape. BurnPro uses topography, historic weather, maps of fuels, and historic ignition locations to estimate the likelihood of burning given the speed and direction a fire might burn from any ignition point, the length of the fire season, and the frequency of fire-stopping rain events during the fire season.

The most important variable in determining the probability of burning for a given area is the number of neighboring locations that burn. To evaluate how suppression of lightning-caused fires on lands outside of a WFU area might affect the rate of burning within the WFU area, probability of burning was determined using two different ignition scenarios: 1) all lightning ignitions and 2) only those lightning ignitions that occurred within the WFU area. For each study unit the reduction in probability of burning due to the suppression of lightning-ignited fires outside of the WFU area was mapped to identify areas where restoration objectives can be most easily met through natural ignitions, versus areas where managers will face more difficult challenges in restoring fire regimes through the use of natural ignitions.



All lightning ignitions in Sequoia/Kings Canyon study area (left) and ignitions only within WFU area. Notice difference in ignition count.



Sequoia-Kings Canyon study area: Reduction in probability of burning in the WFU area with suppression of natural ignitions outside of WFU area. Areas with high % reduction (circled) are areas where it may be especially difficult to restore fire to a natural frequency due to suppression on adjacent lands.

Results and Discussion:

- Estimates of probability of burning across the landscape can help identify areas with the greatest opportunities for WFU. If the decision to suppress a fire is made in areas with a higher probability of burning, there is a good chance that there will be another opportunity for WFU use in these areas soon. In contrast, in areas with a low probability of burning, the chance for WFU does not occur often. Suppression should be avoided in areas where WFU is the preferred strategy whenever possible.

- The suppression of lightning-ignited fires outside of a WFU area can greatly decrease the rate of burning in some places within the WFU area (see map at left) as a result of the unique spatial configuration of fuels, topography, and ignitions.

- Estimates of probability of burning can improve risk assessments and help prioritize fuels treatments. Areas that have a high probability of burning and contain a value-at-risk, such as the wildland-urban interface or critical habitat for a listed species, are given a high priority for fuels treatment.

Management Implications:

- Estimates of probability of burning can be combined with spatial information on the social and ecological values that may be affected by fire, and used in designing strategic fire and fuels management plans, including prioritizing fuels treatments.
- To restore natural fire regimes to WFU areas with a significantly lower probability of burning due to the suppression of fires outside of the area managed for WFU, periodic prescribed burning may be necessary.
- Site-specific information of the kind used in this study can be used to directly support the development of Fire Management Plans (FMPs) or the evaluation of current FMPs as they apply to wilderness and other unroaded areas.

Publications / Products:

- Davis, Brett, Carol Miller. 2004. Modeling Wildfire Probability Using a GIS. In: Proceedings of the ASPRS 2004 Annual Conference, Denver, USA. May 23-28. American Society for Photogrammetry and Remote Sensing, 2004. Available on CD only. **Leopold Publication Number 509.**
- Miller, Carol. 2003. The spatial context of fire: a new approach for predicting fire occurrence. Pages 27-34 in K.E.M. Galley, R.C. Klinger, and N.G. Sugihara (eds.). Proceedings of Fire Conference 2000: The First National Congress of Fire Ecology, Prevention, and Management. Miscellaneous Publication No. 13, Tall Timbers Research Station, Tallahassee, FL. **Leopold Publication Number 501**.

For additional information…

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This summary prepared by N. Queener 12/04.

Guidebook - *Draft*

Sample of Chapter 2 (methods and guidebook) from review draft of final report to Great Smoky Mountains National Park.

Chapter 2 Methods and Guidebook

Introduction

This chapter is intended to be a guide for replicating the results we obtained using the model BurnPro and/or for modeling additional scenarios to explore the effect of alternative fire management strategies. This chapter assumes that the reader has basic GIS and spreadsheet skills. Experience and skill working with fire behavior models and fire weather analyses would also be useful. If the user has no fire-modeling skills s/he will need to familiarize her/himself with the proper use of the software packages used. Substantial preparation of the data is necessary, and involves use of the fire analysis tools FireFamilyPlus and FlamMap. Much of the data referred to accompanies this report and are ready to use. See Appendix...

BurnPro is a GIS model that estimates the annual probability of burning for every pixel on a raster landscape. BurnPro uses topography, historic weather, current fuel model data and historic ignition locations to estimate the likelihood of burning given the speed and direction a fire might spread from any ignition point. It computes the probability of burning a location as the product of the probability that fire reaches the location before the end of the fire season and the probability that fire will reach the location before a fire-stopping event. As such, it integrates the timing and location of ignitions, rate of spread of fire (as it is affected by fuels, topography and weather), length of fire season as it varies over elevation, and frequency of fire-stopping events (i.e., rain) during the fire season.

BurnPro is intended to support long-term processes such as fire management planning. It is not suitable for most incident management applications, but can be useful for the type of pre-planning that supports a go/no-go decision. For more details on BurnPro, please see 'Modeling Wildfire Probability Using a GIS' (Davis, B. and C. Miller. 2004) in Appendix *

Software and Hardware requirements

Software Requirements: ArcInfo Workstation, FlamMap, FireFamilyPlus , spreadsheet program like Excel.

Hardware Requirements: Follow the system requirements for ArcInfo Workstation (http://www.esri.com/software/arcgis/arcinfo/about/systemrequirements.html) and FlamMap (http://fire.org/nav.mas?pages=flammap&mode=16). As always, more is better, especially for large study areas.

Data Requirements

Before acquiring data it is necessary to define two parameters. First, you must define your *study area* which will likely depend on data availability. Ideally, your GIS data layers will encompass a large buffer (e.g. 10 kilometers) around your true area of interest (e.g., a National Park). In reality, this is very difficult to find, and therefore you should use the maximum buffer possible. Second, you must define the length of your *fire season*. The fire season should be defined in whole months and its length should be the known length at the lowest elevation in your study area (e.g., June-September). Currently the longest fire season that BurnPro accommodates is five months. There are ways to extend this but they are not covered in this guide.

The basic data required to prepare for and to run BurnPro includes:

- historic ignition points
- daily historic weather data from Remote Automated Weather Stations (RAWS) or similar weather stations
- current fuel type data
- topographic data (elevation, slope and aspect)
- boundaries delineating the study site and other areas of interest
- three additional data files (see 'Additional data files' section below).

Each of these data sets is described below and all required data are provided for each of our study areas on the accompanying cd. To apply BurnPro to a different study site, it may be necessary to acquire new data. Modifying model parameters may also require new data and/or further manipulation.

General guidelines for all data collection and preparation:

•attempt to get data that extends beyond the area of interest,

•resample to ***common cell size*** *(if raster data) and*

*•**re-project** all data to a common projection*

Historic Ignition Points (NIFMID/SACS)

Acquiring historic ignition data

Historic ignition data resides in the National Interagency Fire Management Integrated Database (NIFMID) for USDA Forest Service lands. Historic ignitions for the Department of the Interior lands (NPS, BLM, FWS and BIA) reside in the Shared Applications Computer System (SACS). Ignition data from both of these databases can be obtained from the National Wildfire Coordinating Group's (NWCG) 'Fire & Weather Data' website (http://famweb.nwcg.gov/weatherfirecd/).

There are numerous, well-documented shortcomings of these data, many of which you can find outlined in the Program for Climate, Ecosystem and Fire Application's (CEFA) 'Coarse Assessment of Federal Wildland Fire Occurrence Data' (http://www.cefa.dri.edu/Publications/fireoccurrencereport.pdf). In addition to this report, CEFA has developed a database of federal ignition points in which some of the grossest errors have been corrected or flagged. The majority of the ignition data used in this project were obtained from this database. To obtain these data, use the contacts listed in the CEFA report.

It is important to have both extensive and accurate records in order to capture historic ignition patterns. In general, locational accuracy of ignition points decreases the further back in time you go. Therefore it is necessary to make a compromise between the number of years of ignition data used and the accuracy of ignition location. For example, in most of our study areas we used 1986 through the most current year available. We chose 1986 as a cut off date because this is the year when many agencies began reporting ignition location as points (latitude / longitude) rather than as within an area (township, range, section). In addition, it is necessary to decide if there is a particular type of ignition you are interested in (e.g. lightning, human-caused or both).

Preparing historic ignition data

Before they can be input into BurnPro the ignitions of interest must be extracted from the source data and converted into an ArcInfo point coverage. This extraction may include spatially selecting the ignitions of interest (e.g. by clipping them with the study boundary) and/or the selection of the ignitions of interest (e.g. lightning caused ignitions). In addition the ignitions must be separated into month of occurrence, one point coverage for each month in the fire season

Historic Weather Conditions

Acquiring historic weather data

Daily weather data are required to develop the information that BurnPro needs on historic weather conditions. Daily weather data can be obtained most easily from the NWCG's website (http://famweb.nwcg.gov/weatherfirecd/).

The first step is to select which weather station(s) you want to use. This should be defined by someone familiar with the area and preferably with fire modeling experience (FARSITE, FlamMap etc.). General considerations to keep in mind include selecting stations that are representative of the area as a whole and have complete and extensive records.

The station(s) selected should be elevationally and spatially representative. If you are using one station its elevation should be near the average elevation of the study area, if using more than one station the average elevation of the stations should be near the average elevation of the study area and should have a variety of elevations (e.g. one low, one mid and one high). Better yet, the station(s) should be elevationally near the average elevation of just those portions of the study area that have burnable fuels because those are the areas of interest.

Station selection should also be spatially representative of the study area. In other words, if you are using one station it is preferable to have it located near the center of the study area. If using more than one station, they should be as evenly spread across the study area as possible rather than clumped together.

Stations should also have complete records. There should be no large gaps in the daily records for the months of the fire season. You can look for gaps by opening the weather files in Excel (see below for instructions on manipulating weather data into a format that can be imported into Excel easily) and obtaining record counts by year/month. They should also be as extensive, in terms of length of record, as possible. It is recommended that you use at least 20 years worth of data and definitely no less than 10. The available years for each station are listed on the NWCG website. The goal is to capture the variability in weather conditions for the area in order to predict what might be expected in the future.

Of course locating stations that fit all these requirements exactly would be nearly impossible. But it is important to adhere to them as closely as possible keeping in mind that the further they are deviated from the less accurate the results will be.

Once you have selected your station(s) download the weather files (*.fwx) and the catalog files (*.txt) from the NWCG website (or other source).

Preparing historic weather data

The weather data need to be summarized to provide the information about historic weather conditions required by BurnPro. This information is used to establish the frequency of fire-stopping weather events, determine the frequency distribution of wind directions, and to predict rate of spread of fire.

Fire stopping event frequency. BurnPro requires the average annual number of fire-stopping events for each month in the fire season. A fire-stopping event is defined as the quantity of rain necessary to extinguish or severely curtail the spread of a wildfire. For example, ‘0.5 inches in 5 days or less’ was used for all our study areas except the Great Smoky Mountains National Park. This number was selected based on analysis in ‘Probability of Fire-Stopping Precipitation Events’ (Latham and Rothermel, 1993) a copy of which can be found in the appendix. Note that this particular definition may not apply to all study locations and the values chosen should be reflective of local conditions. For example, we used '1.5 inches of rain in 5 days or less' for Great Smoky Mountains National Park based on feedback from local managers.

Wind direction distribution. BurnPro requires information on the historic distribution of wind directions for the study area. This is simply how often the wind blows from a particular direction (e.g. Southwest – 50% of the time, South – 10% etc.).

Weather data for ROS calculations. Finally, historic weather data need to be summarized for FlamMap to calculate the Rate Of Spread (ROS) values that are required by BurnPro. FlamMap's specific requirements for weather data are outlined below in the section on creating FlamMap input files.

FireFamilyPlus

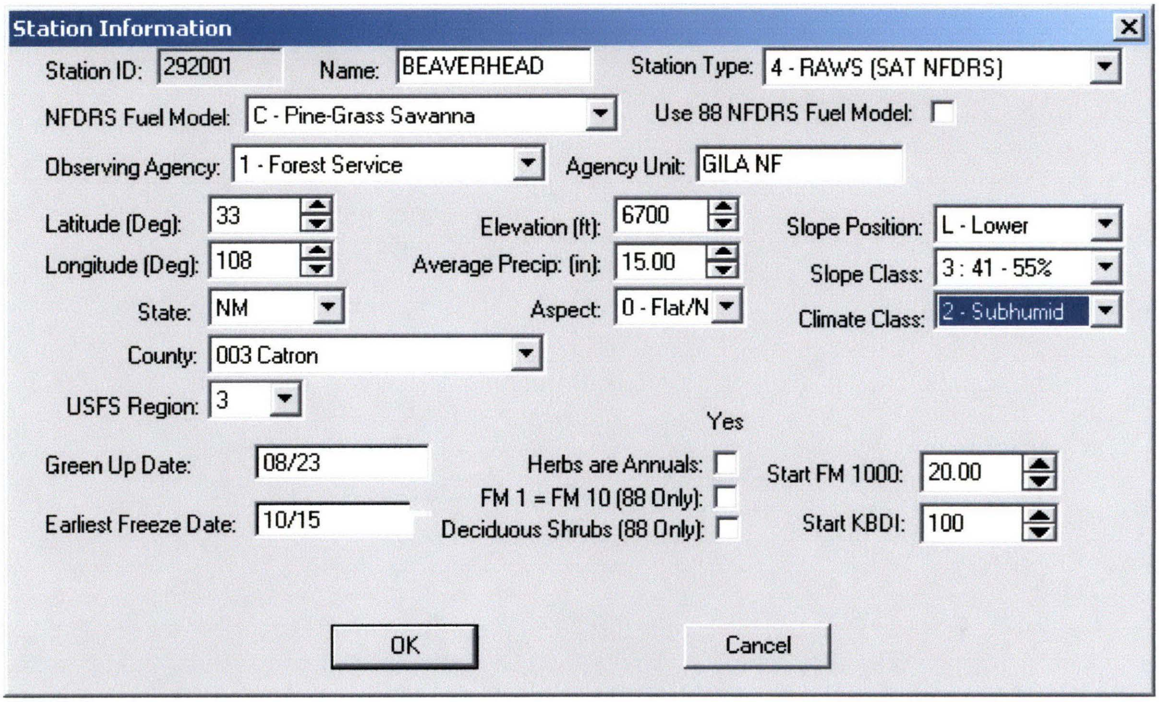
Much of the weather data summarization requires the use of FireFamilyPlus (FFP). FFP is a fire climatology and occurrence program freely available from the fire.org website (http://fire.org/mason/nav.cgi?pages=ffp&mode=1). If you are unfamiliar with FFP it is highly recommended that you obtain the users guide and familiarize yourself with its basic operations before proceeding.

Step One – Load the data.

The following will need to be repeated for each weather station used:

- Import the weather and catalog files into FFP. These files come from the NWCG website or another source.
- Verify that all station information is correct (elevation, location, etc.)
- You can edit the station information via the Station Information dialog box (Figure 3). Green-up and freeze dates are especially important due to their effect on herbaceous fuel moistures.

Figure 3. FFP station information dialog box.

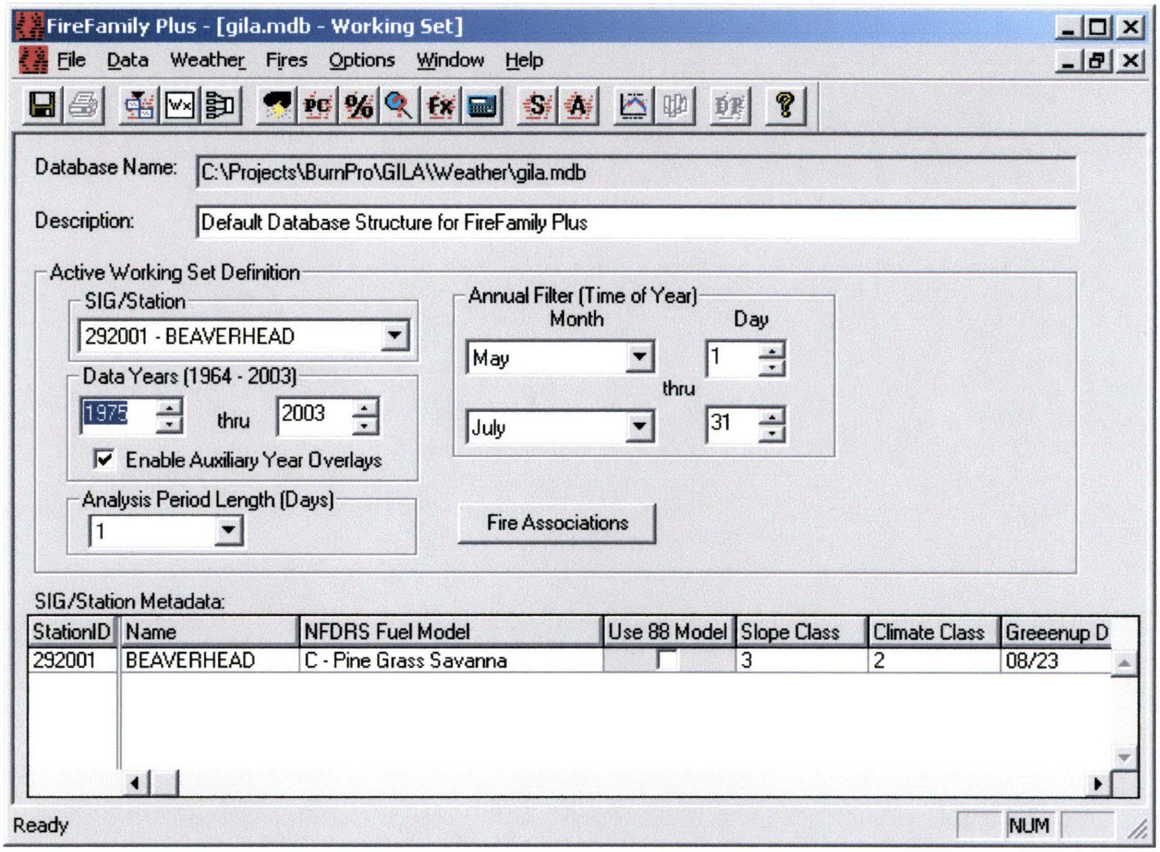


Station ID: 292001
Name: BEAVERHEAD
Station Type: 4 - RAWS (SAT NFDRS)
NFDRS Fuel Model: C - Pine-Grass Savanna
Use 88 NFDRS Fuel Model: ☐
Observing Agency: 1 - Forest Service
Agency Unit: GILA NF
Latitude (Deg): 33
Longitude (Deg): 108
State: NM
County: 003 Catron
USFS Region: 3
Elevation (ft): 6700
Average Precip: (in): 15.00
Aspect: 0 - Flat/N
Slope Position: L - Lower
Slope Class: 3 : 41 - 55%
Climate Class: 2 - Subhumid
Green Up Date: 08/23
Earliest Freeze Date: 10/15
Yes
Herbs are Annuals: ☐
FM 1 = FM 10 (88 Only): ☐
Deciduous Shrubs (88 Only): ☐
Start FM 1000: 20.00
Start KBDI: 100

Step Two—Define your 'Working Set' (Figure 4).

Set the 'Data Years' as desired (e.g. 1985-2003). Then set the 'Annual Filter' to the length of the fire season. This will be the known length of fire season at the lowest elevation for the study area and must comprise whole months (e.g. May 1st – September 31st).

Figure 4. FFP working set definition.


FireFamily Plus - [gila.mdb - Working Set]
File
Data
Weather
Fires
Options
Window
Help
Fire Associations
Ready
NUM

Database Name: C:\Projects\BurnPro\GILA\Weather\gila.mdb

Description: Default Database Structure for FireFamily Plus

Active Working Set Definition

SIG/Station: 292001 - BEAVERHEAD

Data Years (1964 - 2003): 1975 thru 2003

☑ Enable Auxiliary Year Overlays

Analysis Period Length (Days): 1

Annual Filter (Time of Year): Month May, Day 1 thru Month July, Day 31

SIG/Station Metadata:

StationID	Name	NFDRS Fuel Model	Use 88 Model	Slope Class	Climate Class	Greenup D
292001	BEAVERHEAD	C - Pine Grass Savanna	☐	3	2	08/23

Step Three—Extract variables.

The next step is to export the following data via the following menu selections: Weather→ Season Reports→ Daily Listing (Figure 5). This will need to be repeated for each weather station.

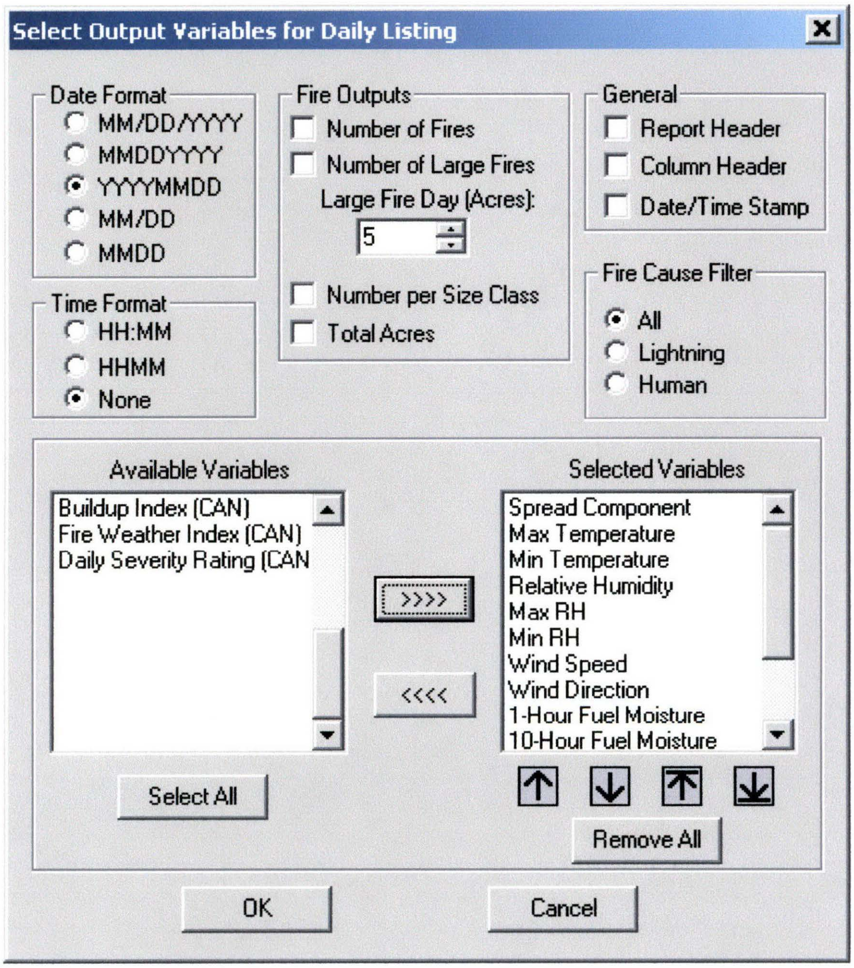
Select the following variables for export (in this order):

- Date (Date Format: YYYYMMDD),
- Spread Component,
- Max Temperature,
- Min Temperature,
- Relative Humidity,
- Max Rh,
- Min Rh,
- Wind Speed,
- Wind Direction,

- 1-Hour Fuel Moisture,
- 10-Hour Fuel Moisture,
- 100-Hour Fuel Moisture,
- Herbaceous Fuel Moisture and
- Woody Fuel Moisture.

Uncheck Date/Time stamp, column header and report header. Hit 'OK' and save the resultant 'daily listing' window as a text file.

Figure 5. FFP daily listing dialog.



Select Output Variables for Daily Listing

Date Format
○ MM/DD/YYYY
○ MMDDYYYY
● YYYYMMDD
○ MM/DD
○ MMDD

Time Format
○ HH:MM
○ HHMM
● None

Fire Outputs
☐ Number of Fires
☐ Number of Large Fires
Large Fire Day (Acres): 5
☐ Number per Size Class
☐ Total Acres

General
☐ Report Header
☐ Column Header
☐ Date/Time Stamp

Fire Cause Filter
● All
○ Lightning
○ Human

Available Variables
Buildup Index (CAN)
Fire Weather Index (CAN)
Daily Severity Rating (CAN

Selected Variables
Spread Component
Max Temperature
Min Temperature
Relative Humidity
Max RH
Min RH
Wind Speed
Wind Direction
1-Hour Fuel Moisture
10-Hour Fuel Moisture

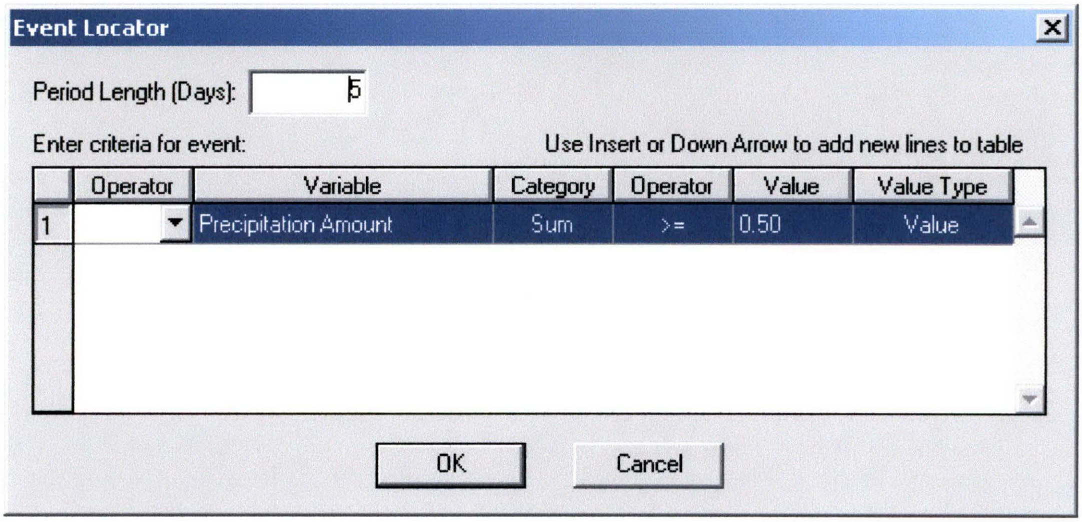
Step Four—Fire Stopping Events.

The Event Locator in FFP is used to find the occurrences of a fire-stopping event. For most Western US areas this should be around 0.5 inches within a five-day period. Make sure that the ‘Annual Filter’ in the FFP working set definition window (Figure 4) is set to the length of the fire season. Use: Weather→ Event Locator. The parameters should be set as follows (Figure 6),

- Period length: number of days (e.g. 5),
- Operator: blank,
- Variable: precipitation amount,
- Category: sum,
- Operator: >=,
- Value: inches of rain (e.g. 0.5) and
- Value Type: value.

Hit ‘OK’ and save the resultant events window as a text file. Repeat for each weather station.

Figure 6. FFP event locator.



Period Length (Days): 5

Enter criteria for event:

Use Insert or Down Arrow to add new lines to table

	Operator	Variable	Category	Operator	Value	Value Type
1		Precipitation Amount	Sum	>=	0.50	Value

Open the fire-stopping event file in a text editor (e.g. notepad) and delete the header, footer and the ‘/’s from the file (use find and replace for the ‘/’s). The following is an example of what the cleaned up file should look like (Table 1):

Table 1. Fire stopping event file.

DATE	Rain
08251979	0.50
10071981	1.38
09131982	0.56
09201982	0.74
09261982	1.22
...	

Cleaning Up Weather Data

The following steps will clean up the weather data you just extracted using FFP.

Step One-Delete blank records:

- Import the 'daily listing' files into a spreadsheet program such as Excel. Choosing fixed width and setting your own delimiters seems to work best (imported columns are right-justified, so set the divider on the right of the column header).
- Look for and delete blank rows in the data. This is important because any sorting you do of the data may only include those rows above the first blank row. The easiest way to accomplish this is to select all data by clicking the area to the left of column A and above row 1 and choose Sort→Ascending, scroll down to the last rows and delete the blank lines.
- Save as an Excel spreadsheet.

Step Two-Verify weather data:

- Verify the weather data by iteratively sorting all records by *each column*, ascending and descending, and look for missing and/or erroneous data.
- Delete records with missing data *with the exception of maximum and minimum relative humidity.* Maximum and minimum relative humidity are commonly missing and it may be necessary to estimate the missing values later using a technique described below. Therefore *do not delete records on account of missing maximum or minimum relative humidities.* Most of the problem data should be located in the first and last few rows after each sort.

Some common data problems include:
-missing data,

-wind direction is not zero when wind speed is zero,
-impossible values (e.g. relative humidities greater than 100%) and
-improbable data (e.g. temperatures greater than 130 degrees or less than -50 degrees Fahrenheit).

- Basically, look for data that doesn't make sense given your familiarity with the study area.
- Re-sort by DATE ascending when finished verifying data.
- Create a column called YEAR and populate it from the date column using the left function[e.g. LEFT(DATE,4)].
- Create a column called MONTH and populate it from the date column using the left and right functions [e.g. RIGHT(LEFT(DATE,6),2)].

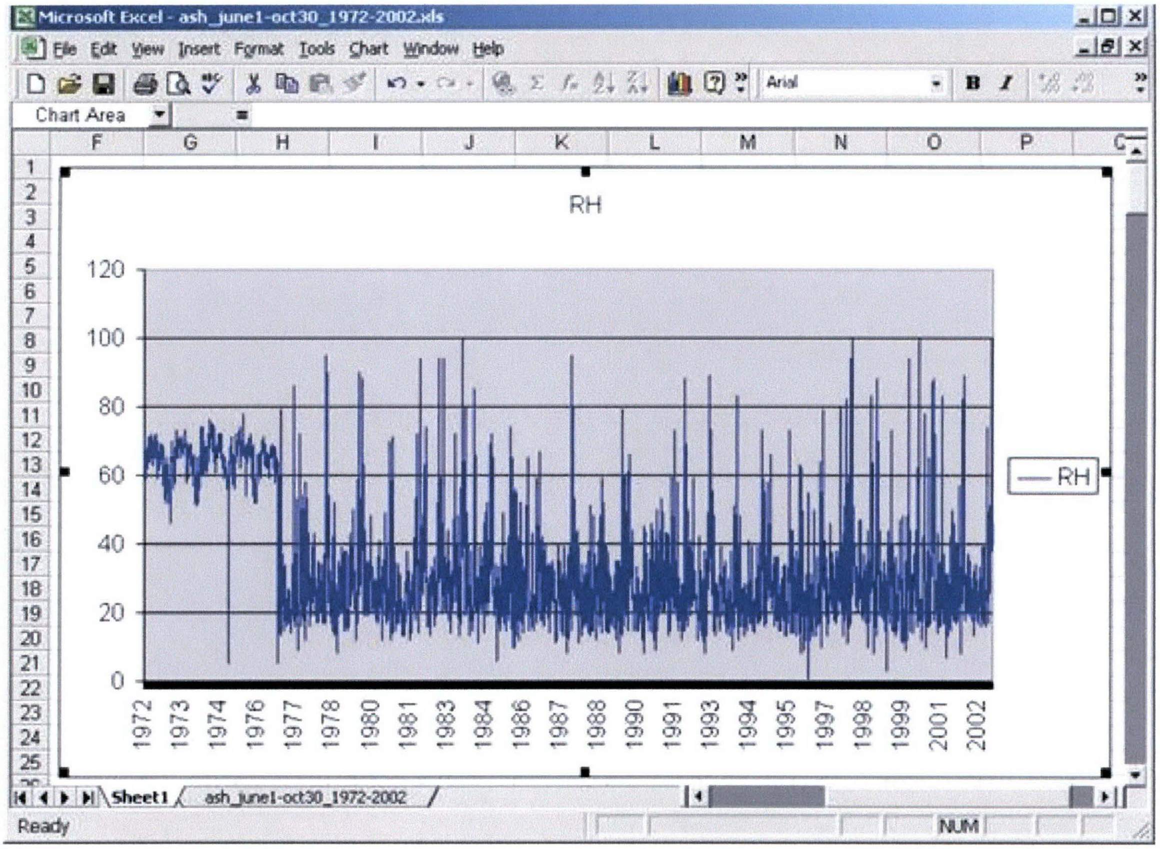
It is a good idea to check whether the numbers of records for each month are in approximately the correct proportion to each other. Missing records are unavoidable but if too many are missing from one month versus the others it will skew the weather calculations. Here's an example:

	Total Records	June	July	August
Station 1	2461	806	816	839
Station 2	2088	452	807	829

Station 1 looks good but station 2 is out of proportion. If the data is used as is the final weather averages will be skewed towards July and August conditions. If you are not comfortable with this then adjustments will be necessary. One possibility would be to separate the data out by month, calculate all averages and average the monthly results together. In this way each month would receive the same weight regardless of the number of records. This technique has not been attempted and therefore there could present unexpected difficulties.

- Create a chart (graph) of YEAR vs. RH to determine whether the methods for data collection have remained the same over the years. It might be wise to do quick eyeball checks of YEAR charted versus other variables to look for other potential errors. In the example shown in figure 7, it is clear that in 1977, something changed in the way RH was collected. Because relative humidity is used to calculate fuel moistures and spread component it is necessary to have consistent collection parameters. Therefore, any data that was apparently collected using different parameters (e.g. the pre 1977 data in Figure 7) should be deleted from your dataset.

Figure 7. Graph of relative humidity.


Microsoft Excel - ash_june1-oct30_1972-2002.xls
File Edit View Insert Format Tools Chart Window Help
Arial
Chart Area
RH
120
100
80
60
40
20
0
1972
1973
1974
1976
1977
1978
1980
1981
1983
1984
1986
1987
1988
1990
1991
1993
1994
1995
1997
1998
1999
2001
2002
RH
Sheet1
ash_june1-oct30_1972-2002
Ready
NUM

Step Three-estimate missing humidity values.

As mentioned above, minimum and maximum relative humidity values are often missing from the data record. You may decide that without these values, you have insufficient data to summarize. In such cases, it is necessary to estimate the missing values using the relationship between relative humidity (RH) which is the relative humidity gathered at a set time in the afternoon (usually 2-3pm) and each of the relative humidity extremes (maximum and minimum, Rhmax and RHmin) for those records in which all three were collected. In order to do this it is necessary to have at least a few years in which all three variables were collected.

For example:

- Select RH, MxRH and MnRH from those rows that contain maximum and minimum relative humidities and paste them into a new worksheet.

- Add two new columns to the new worksheet called MxRH/RH and MnRH/RH populate them with those ratios (e.g. maximum relative humidity divided by relative humidity).
- Determine the average ratios (e.g. average maximum relative humidity = 2.10 times relative humidity and minimum relative humidity = 0.75 times relative humidity).
- Use these two ratios to populate those MnRH and MxRH cells that have no values in the main worksheet.

> Note: It is important that you ensure that these estimates for missing values do not cause maximum relative humidity to exceed 100%. You can ensure this by using an 'IF' statement when calculating maximum relative humidity. MxRH = IF(RH * 2.10 > 100, 100, RH * 2.10) which, in effect, says "if the ratio times relative humidity is greater than 100 put 100, if not put ratio times relative humidity". Again, we are calculating the missing values because eliminating the records without these values would leave us with too few records. Although it hasn't been tested, it might be possible to increase accuracy of these estimates by calculating the relationship for individual months in the fire season and using these monthly relationships instead to calculate the missing values.

Summarizing Weather Data: Percentile Categories

Now that the weather data is cleaned up, you are ready to start the process of summarizing it.

Step One--Defining Percentile Weather Categories

Percentile weather refers to the frequency of occurrence of a particular set of weather conditions in the historical record. In our case Spread Component (SC) defines these weather conditions.

> "Spread Component is a numerical value derived from a mathematical model that integrates the effects of wind and slope with fuel bed and fuel particle properties to compute the forward rate of spread at the head of the fire."
>
> "The inputs required to calculate Spread Component are wind speed, slope, fine fuel moisture (including the effects of green herbaceous plants), and the moisture content of the foliage and twigs of living, woody plants." (Schlobohm, 2002)

For example, if you used FFP to calculate SC for a group of 100 weather records and then sorted or ranked the records by SC value, the record ranking 99th would be the one whose value for SC was higher than all but one record. This would be the 99th percentile SC. Furthermore, the set of weather conditions that resulted in this 99th percentile SC would be the 99th percentile weather conditions. Rather than using percentile weather *conditions*, we elected to use percentile weather *categories*. We determined the weather conditions for each category by taking the average of each weather condition in that percentile category. For example, to determine these conditions for the 99th to 100th percentile weather category we averaged all the weather conditions that resulted in the top 1% of all SCs.

The majority of fire spread occurs under the more extreme weather conditions (low relative humidity, high winds etc.), and concomitantly, under high SC conditions. Therefore, percentile weather categories should be defined with an emphasis on the upper percentiles. We found that four categories are a good compromise between accuracy and processing time. For example, many of our study sites were run with the following percentile weather categories: 0-79, 80-89, 90-97 and 98-100.

> BurnPro predicts *average* annual probability of burning and therefore defining narrow upper percentile categories does not mean that the results are being skewed towards the more extreme conditions. BurnPro performs a weighted average of the probability predictions resulting from each percentile category. The weights given to each prediction are based on the size of the percentile weather category, where the 0-79 category is 8 times "larger" than the 80-89 category. For example, if the probability of burning for a particular place on the landscape was 0.10 for the 0-79 category, 0.20 for the 80-89 category, 0.40 for the 90-97 category and 0.80 for the 98-100 category, the average annual probability prediction would be (0.10 * 0.80) + (0.20 * 0.10) + (0.40 * 0.07) + (0.80 * 0.02) = 0.144..

Step Two--Calculating Average Percentile Weather Conditions

Next, it is necessary to determine the average weather conditions that represent each of the percentile categories.

- Sort the data by SC descending.
- Determine spread component percentile cutoffs using Excel's PERCENTILE function which is of the form: PERCENTILE(*Array,k*). Where *Array* is the range of SC values and *k* is the percentile of interest. For example,

PERCENTILE(A2:A3000, 0.99) would calculate the 99th percentile SC for the range of SCs found in cells A2 through A3000.

- Use the inclusive cutoffs to obtain subtotals (average function) for the following variables: maximum temperature, minimum temperature, relative humidity, maximum relative humidity, minimum relative humidity, all five fuel moistures categories and wind speed. For example, if one of your percentile weather categories was 0-79, and you calculated the 79th percentile SC = 5, you would need to calculate the average temperatures, humidities, fuel moistures and wind speeds for those records with a SC between 0 and 5.
- Copy all the average results to a new "RESULTS" worksheet.
- Clear the average subtotals.
- Obtain overall counts (using subtotals with the count function) of each wind direction and calculate the percentage that they represent. For example, if 4000 of 8000 records indicate southwest winds then winds are out of the southwest with a frequency of 0.50 (50% of the time). It is necessary to use the count function rather than the average function because wind is a discrete rather than continuous variable.

Note: wind direction value of 0 = calm, 1 = NE, 2=E, 3=SE, 4=S, 5=SW, 6=W, 7=NW, 8 = N.

- Copy the wind direction count results to the RESULTS worksheet.
- Repeat the above processes for each weather station.
- Calculate the average values across weather stations (see Table 2 for an example).

Table 2. Average weather conditions by percentile weather conditions.

Station	MaxT	MinT	RH	MxRH	MnRH	Wind	FM1	FM10	F100	FMH	FMW	CATEGORY
Station 1 9953ft												
	63.50	40.10	12.45	25.25	9.00	8.65	2.45	2.85	4.75	2.45	60.00	98-100
	75.23	45.84	12.00	31.72	9.86	5.52	2.29	2.96	4.62	2.29	60.00	90-97
	77.02	46.70	14.68	36.47	11.65	3.93	2.72	3.34	5.44	2.72	60.00	80-89
	76.69	49.34	33.37	63.55	24.20	1.80	6.39	7.33	9.63	6.39	60.00	0-79
Station 2 6700ft												

75.72	35.12	17.50	65.05	14.04	21.26	3.56	5.52	9.70	3.56	60.00	98-100
79.40	35.89	17.72	67.08	14.23	14.60	3.59	5.50	9.35	3.59	60.00	90-97
81.00	37.73	17.34	64.51	13.72	10.64	3.53	5.34	8.69	3.53	60.00	80-89
81.40	43.66	27.28	76.81	20.99	5.58	5.92	9.92	10.85	5.92	60.00	0-79

Station 3
5600ft

84.24	37.06	17.24	56.01	12.15	21.57	3.26	4.33	9.94	3.26	50.93	98-100
84.59	36.93	14.96	49.34	10.56	14.33	3.01	5.03	8.42	3.01	52.48	90-97
86.10	37.98	14.89	49.36	10.46	11.08	3.08	5.14	8.34	3.08	52.97	80-89
86.64	43.88	29.51	75.97	20.64	5.32	5.77	8.55	12.10	5.77	51.63	0-79

Avgerage
(7418ft)

74.49	**37.43**	**15.73**	**48.77**	**11.73**	**17.16**	**3.09**	**4.23**	**8.13**	**3.09**	**56.98**	**98-100**
79.74	**39.55**	**14.89**	**49.38**	**11.55**	**11.48**	**2.96**	**4.50**	**7.46**	**2.96**	**57.49**	**90-97**
81.37	**40.80**	**15.64**	**50.11**	**11.94**	**8.55**	**3.11**	**4.60**	**7.49**	**3.11**	**57.66**	**80-89**
81.58	**45.62**	**30.05**	**72.11**	**21.94**	**4.23**	**6.03**	**8.60**	**10.86**	**6.03**	**57.21**	**0-79**

Wind Direction	Station 1	Station 2	Station 3	**Average**
North	0.15	0.12	0.05	**0.11**
Northeast	0.12	0.07	0.06	**0.08**
East	0.07	0.09	0.03	**0.07**
Southeast	0.12	0.19	0.15	**0.15**
South	0.15	0.21	0.24	**0.20**
Southwest	0.15	0.14	0.30	**0.20**
West	0.11	0.08	0.11	**0.10**
Northwest	0.11	0.10	0.06	**0.09**

With the exception of wind direction, all values will be used to create input files for FlamMap. The wind direction information will be input into BurnPro directly.

Create FlamMap Input Files

The average values for the weather percentile categories will be used to create the following FlamMap input files: initial fuel moisture (.FMS) files, weather (.WTR) files and wind (.WND) files. *One of each will be created for each percentile weather category.* The .WTR and .WND files are used to condition the initial fuel moistures. In other words, FlamMap sets the initial fuel moistures according to the .FMS file and then simulates what they would change to after being exposed to the conditions in the weather and wind files. With conditioning, FlamMap calculates "...dead fuel moistures for each cell based on topography, shading, weather and conditioning period length" (FlamMap, 2004)

Use a text editor (e.g. notepad) to create the files following these formats (see either FlamMap or FARSITE help for more information on these files (FlamMap, 2004). Be sure to name the files with the proper extension (.fms, .wtr or .wnd)

Fuel Moisture File Format:

FuelMod 1Hour 10Hour 100Hour LiveH LiveW

Repeat with same values for all fuel types represented in your fuels data. E.G.

```
1 3 5 7 8 60
2 3 5 7 8 60
4 3 5 7 8 60
5 3 5 7 8 60
6 3 5 7 8 60
8 3 5 7 8 60
9 3 5 7 8 60
10 3 5 7 8 60
11 3 5 7 8 60
12 3 5 7 8 60
13 3 5 7 8 60
14 3 5 7 8 60
18 3 5 7 8 60
28 3 5 7 8 60
```

Weather File Format:

Month Day Precip Hour1 Hour2 MinTemp MaxTemp MaxRh MinRh Elev

Always place zeros under Precip. Hour1 is the time of the minimum temperature and Hour2 is the time of the maximum temperature. Elevation should be the average elevation of the weather stations. Repeat for the number days you want to condition the fuels before running FlamMap. It is recommended that you condition fuel moistures for three to five days. The actual dates used are irrelevant as long as they are consecutive. E.G.

```
7  1   0 0500 1500  70  98  49  20  4433
7  2   0 0500 1500  70  98  49  20  4433
7  3   0 0500 1500  70  98  49  20  4433
7  4   0 0500 1500  70  98  49  20  4433
7  5   0 0500 1500  70  98  49  20  4433
```

Wind File Format:

Month Day Hour Speed Direction CloudCover

The development of this file requires some compromises and approximations. Use the same days as the weather files and four-hour intervals. Of those four-hour intervals put your desired wind speed in the 1200 and 1600 intervals and put zeros in the rest. Your direction will always be the most prevalent direction for the study area e.g. 225 (SW). Populate cloud cover with zeros. This file needs to have units defined on first line (English vs Metric) E.G.

```
ENGLISH
7 1 0000  0  225  0
7 1 0400  0  225  0
7 1 0800  0  225  0
7 1 1200  15  225  0
7 1 1600  15  225  0
7 1 2000  0  225  0
7 2 0000  0  225  0
7 2 0400  0  225  0
7 2 0800  0  225  0
7 2 1200  15  225  0
7 2 1600  15  225  0
7 2 2000  0  225  0
.
.
.
7 5 0000  0  225  0
7 5 0400  0  225  0
7 5 0800  0  225  0
7 5 1200  15  225  0
7 5 1600  15  225  0
7 5 2000  0  225  0
```

Repeat the creation of these files for each percentile weather catategory.

Frequency of a Fire-Stopping Event

To determine the frequency of a fire-stopping event, open the fire-stopping event file in Excel, making sure to *import the date column as text*. Sort by date and compute subtotals (counts) for each month. Also note the period of record (i.e., number of years) for each station.

Because these subtotals represent counts of a discrete event (e.g., x inches of rain within a y-day period) they will be distorted by any missing records We want to give each station equal weight when calculating the monthly fire-stopping event probabilities. Therefore, it may be necessary to adjust the frequency calculation.

Consider the following example:

Table 3. Fire stopping event frequency data.

Station 1

	records	days	# yrs	events	pstop
May	300	31	9.68	2	0.21
June	292	30	9.73	10	1.03
July	287	31	9.26	21	2.27

Station 2

	records	days	# yrs	events	pstop
May	806	31	26.00	11	0.42
June	816	30	27.20	12	0.44
July	839	31	27.06	59	2.18

Station 3

	records	days	# yrs	events	pstop
May	827	31	26.68	10	0.37
June	800	30	26.67	15	0.56
July	830	31	26.77	60	2.24

The fire-stopping event probability is being calculated based on three weather stations, Station 1, Station 2 and Station 3. In the table 'records' represents the number of records present for that station/month, 'days' equals the number of days in the month, '# yrs' is the standardized number of years that number of records represents (calculated by dividing 'records' by 'days'), 'events' is the number of times the fire-stopping event occurred within the records (calculated by FFP) and 'pstop' is the frequency of the fire-stopping event (calculated by dividing 'events' by '# yrs'). The calculation of 'pstop' is where the weighing to account for missing records is implemented. The final step is to calculate the average pstop amongst the stations (Table 4).

Table 4. Fire stopping events.

	Station 1	Station 2	Station 3	**Average**
May	0.21	0.42	0.37	**0.33**
June	1.03	0.44	0.56	**0.68**
July	2.27	2.18	2.24	**2.23**

These average values will be directly input into BurnPro.

Current Fuels

The most current fuels data should be obtained for the study site (from the National Forest, Park etc). Fuels should be classified according to Northern Forest Fire Laboratory (NFFL) standards. If the fuels data contains custom fuel models, be sure to obtain their definitions. If at all possible, obtain the 'optional' canopy data (stand height, crown bulk density, crown base height). The canopy data can enhance the accuracy of FlamMap's, and subsequently BurnPro's, predictions.

The fuels data need to be manipulated into the ASCII format for input into FlamMap. This process involves converting all the various fuels data layers (fuel, canopy data) as well as topography data (elevation, aspect and slope). How this is achieved depends on the format in which the original data were acquired. For example, if your fuels data is an ArcInfo grid, you can use the 'gridascii' command to convert it into an ASCII file. It is important to ensure that the original files have a *common projection, format, cell size and origin* (the same minimum X and Y coordinates) before converting them to ASCII files. It is a very good idea to have all these inputs in your desired working cell size (the cell size you want to run BurnPro for) before exporting them to ASCII files.

Topography

Elevation, slope and aspect data are required to run BurnPro. Topography data can be obtained from various sources including the study site and the National Elevation Dataset (NED) http://seamless.usgs.gov/viewer.htm (use the download option). Once you obtain the elevation dataset it can be used to create the slope and aspect data using ArcGIS. These data should be manipulated into the ASCII format and loaded into the landscape file as outlined above for fuels.

Boundaries

Any boundaries of interest, including your analysis area boundary, should be obtained from the study site (National Forest, Park etc.) and typically need no particular manipulation. Examples include: Wilderness, Forest, Park, Fire

Management Zones/Units, etc. These boundaries are used to define study areas (e.g., buffer the area of interest) and to manipulate (e.g., clip) ignition and fuels data.

Additional data files

There are three additional files that are necessary to run BurnPro.

The first file is maxrosdir.rmt. This is a generic remap table that groups 360-degree aspects into eight categorical directions (e.g. North, Northeast, etc.). It allows BurnPro to classify the direction of maximum fire spread predicted by FlamMap into eight categories.

The two other files are sigma.rmt and eta.rmt. These files contain information about the length of fire season over elevation. They are specific to each individual study site and should only be used for that study site, or one with similar characteristics in terms of location and elevation range. Although it is common knowledge that high elevation sites have a much shorter fire season than low elevation sites, to our knowledge, this information does not exist in empirical form. Therefore, we derived this information for each of the study sites. We derived this information by fitting the number of drought-days predicted by the forest dynamics model FACET to the Weibull probability distribution function as described in Miller, C. 2003a. The two files contain the Weibull parameters resulting from that curve fitting exercise. The forest dynamics model FACET was used to calculate the number of drought-days for a range of elevations. This allowed us to develop a relationship between elevation and the number of drought-days, which we used as a proxy for how the length of fire season varies over elevation. Finally, we calibrated this relationship to the maximum length of the fire season (i.e., the length of fire season at the lowest elevation in the study site). We expect to eliminate the use of FACET in the future in favor of a simpler procedure that can be readily implemented by the user.

Running FlamMap

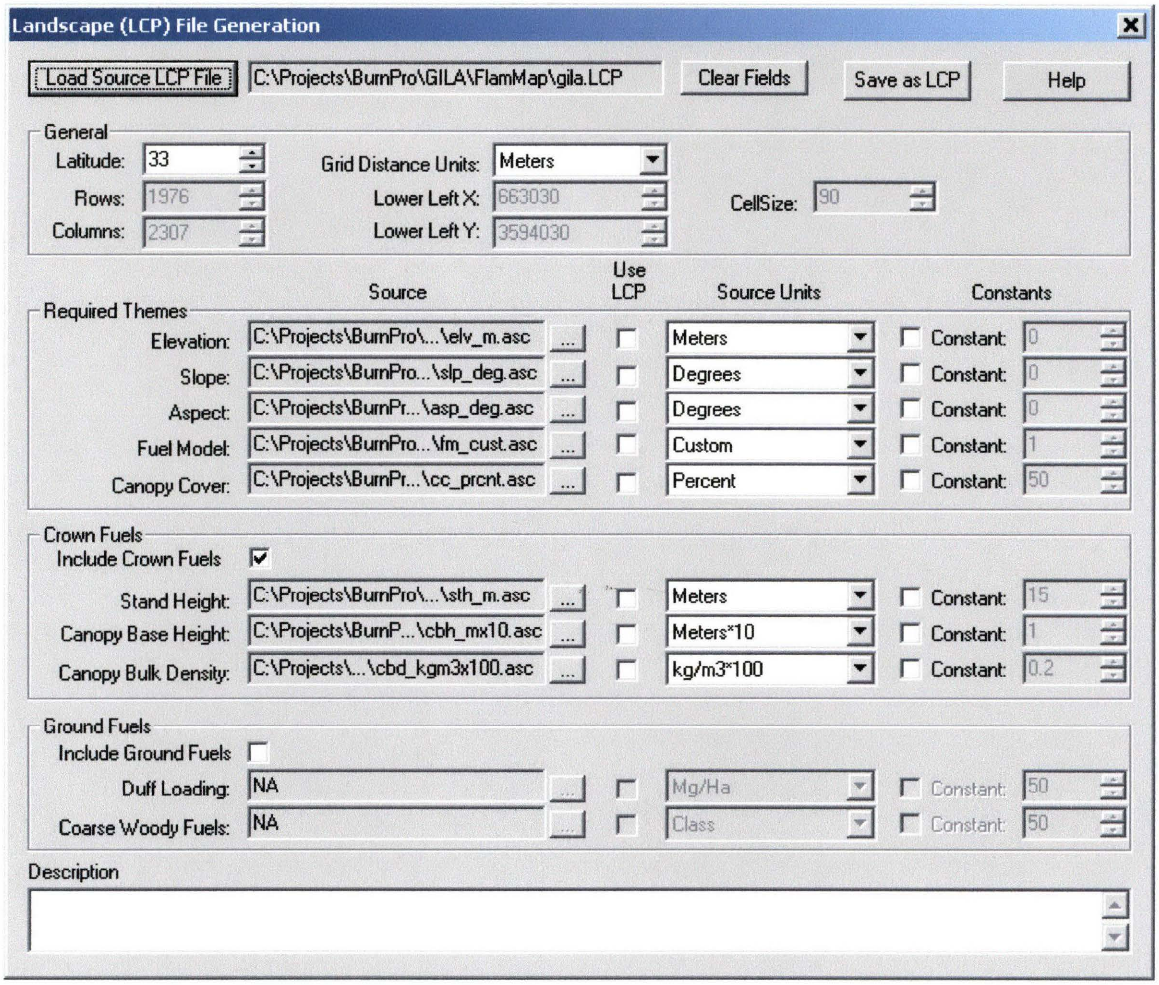
To run BurnPro, you need to generate two fire-behavior data sets with FlamMap. First obtain the latest version of the software:
http://fire.org/nav.mas?pages=flammap&mode=12

The two fire-behavior datasets to be generated are Rate Of Spread (ROS) and Maximum Spread Direction (MSD). Multiple sets of these data need to be created for many combinations of input parameters and will therefore require a substantial amount of time. For example, if you have defined four weather percentile categories, you will run FlamMap 64 times: 4 (weather percentile categories) X 8 (wind directions) X 2 (times of day – 4am & 2pm) = 64 runs. Depending on the speed of your computer and how vigilant you are during the process, this can take 4-8 hours (or more). As mentioned earlier, it is important that you have a basic familiarity with FlamMap. If you don't, it is highly recommended that you use the tutorial provided with the software to gain that familiarity before proceeding.

Create and Load the Landscape File

Create the landscape file using FlamMap (File → Create landscape (LCP) files…). Use the ASCII files you created from the fuels and topography data. Refer to the example in Figure 8.

Figure 8. FlamMap landscape file generation dialog.



C:\Projects\BurnPro\GILA\FlamMap\gila.LCP

General
Latitude: 33
Rows: 1976
Columns: 2307
Grid Distance Units: Meters
Lower Left X: 663030
Lower Left Y: 3594030
CellSize: 90

Required Themes

	Source	Use LCP	Source Units	Constants
Elevation:	C:\Projects\BurnPro\...\elv_m.asc	☐	Meters	☐ Constant: 0
Slope:	C:\Projects\BurnPro...\slp_deg.asc	☐	Degrees	☐ Constant: 0
Aspect:	C:\Projects\BurnPr...\asp_deg.asc	☐	Degrees	☐ Constant: 0
Fuel Model:	C:\Projects\BurnPro...\fm_cust.asc	☐	Custom	☐ Constant: 1
Canopy Cover:	C:\Projects\BurnPr...\cc_prcnt.asc	☐	Percent	☐ Constant: 50

Crown Fuels
Include Crown Fuels ☑

	Source	Use LCP	Source Units	Constants
Stand Height:	C:\Projects\BurnPro\...\sth_m.asc	☐	Meters	☐ Constant: 15
Canopy Base Height:	C:\Projects\BurnP...\cbh_mx10.asc	☐	Meters*10	☐ Constant: 1
Canopy Bulk Density:	C:\Projects\...\cbd_kgm3x100.asc	☐	kg/m3*100	☐ Constant: 0.2

Ground Fuels
Include Ground Fuels ☐

	Source	Use LCP	Source Units	Constants
Duff Loading:	NA	☐	Mg/Ha	☐ Constant: 50
Coarse Woody Fuels:	NA	☐	Class	☐ Constant: 50

Be sure to set the latitude of your study area and make sure all 'Source Units' are correct. As mentioned earlier, some crown fuels layers are optional but they will improve FlamMap's predictions. Ground fuels are not necessary. Load the landscape file into FlamMap (Theme → FARSITE landscape file).

Set FlamMap Options

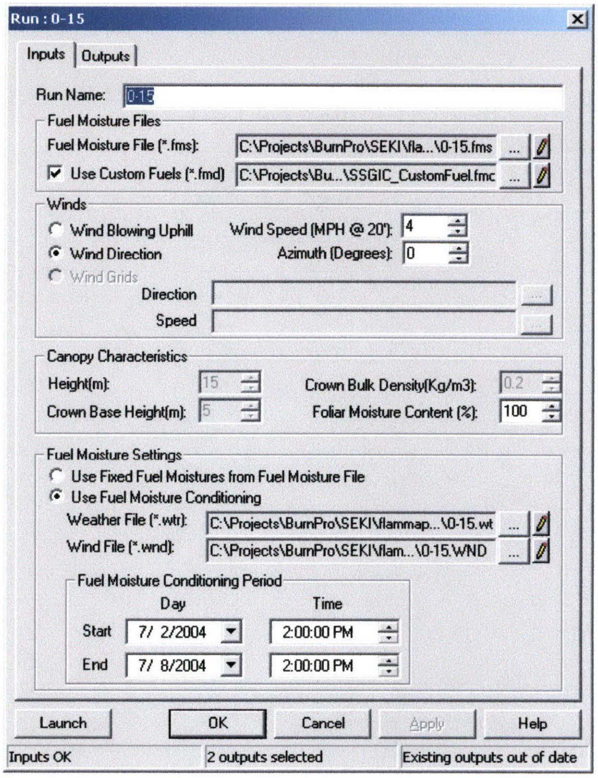
Next, set the following default options (Set Options→ Preferences → Edit Preferences). Under the Max Spread Direction tab set units to degrees, decimals to 0 and number of classes to 9. It is especially important to make sure that maximum direction values are in degrees. If this option is set to radians it will result in erroneous outputs from BurnPro. Under the Rate of Spread tab set units to meters per minute (m/min). Once again, Other units will result in erroneous results.

FlamMap Runs

Once the preferences are set it is time to set up the first FlamMap run (Analysis Area→ New Run or double-click 'run' in the left-hand pane). You will set up one run for each percentile weather category you are using. Set the following parameters: Name the run with the percentile weather category it represents. Load the appropriate fuel moisture file. If you are using any custom fuel types load your fuel model definition (.fmd) file (see FlamMap help for more information on .fmd files). Select the 'Wind Direction' radio button. Enter the average wind speed that you calculated above for this percentile weather category. Set the azimuth to 0. (Wind direction azimuth is the from direction e.g. an azimuth of 0 means the winds are coming from the north and an azimuth of 180 means the winds are coming from the south.) Select the 'Use Fuel Moisture Conditioning' radio button and load the appropriate weather and wind files. The 'Fuel Moisture Conditioning Period' Start and End dates will be the first and last days that were entered in the weather and wind files above. The actual dates are irrelevant but your conditioning period should be around five days. The end time is important. We will use two different end times for our Rate of Spread calculations, 2pm and 4am. BurnPro uses the results at these two times to determine average daily rates of spread. Set the conditioning period end time to 2pm (1400) for now.

Below is an example of how to populate the variables this example is for a 0-15 percentile weather category, north winds, 2pm case (Figure 9).

Figure 9. FlamMap run definition dialog part 1.



Run Name: 0-15

Fuel Moisture Files

Fuel Moisture File (*.fms): C:\Projects\BurnPro\SEKI\fla...\0-15.fms

☑ Use Custom Fuels (*.fmd) C:\Projects\Bu...\SSGIC_CustomFuel.fmc

Winds

○ Wind Blowing Uphill

● Wind Direction

○ Wind Grids

Wind Speed (MPH @ 20'): 4

Azimuth (Degrees): 0

Direction

Speed

Canopy Characteristics

Height(m): 15

Crown Base Height(m): 5

Crown Bulk Density(Kg/m3): 0.2

Foliar Moisture Content (%): 100

Fuel Moisture Settings

○ Use Fixed Fuel Moistures from Fuel Moisture File

● Use Fuel Moisture Conditioning

Weather File (*.wtr): C:\Projects\BurnPro\SEKI\flammap...\0-15.wt

Wind File (*.wnd): C:\Projects\BurnPro\SEKI\flam...\0-15.WND

Fuel Moisture Conditioning Period

	Day	Time
Start	7/ 2/2004	2:00:00 PM
End	7/ 8/2004	2:00:00 PM

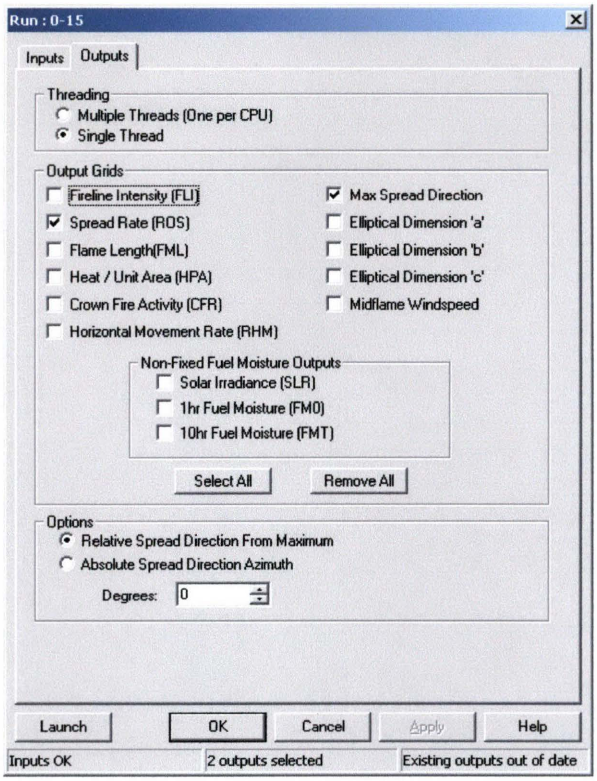
Inputs OK

2 outputs selected

Existing outputs out of date

That completes our 'Inputs' definitions. Click on the 'Outputs' tab to define the out puts. Choose Spread Rate (ROS) and Max Spread Direction (MSD). Note that you only need to check the Max Spread Direction box for the 2pm runs. MSD is not calculated for the 4am runs. See the example below (Figure 10).

Figure 10. FlamMap run definition dialog part 2.



Threading
○ Multiple Threads (One per CPU)
● Single Thread

Output Grids
☐ Fireline Intensity (FLI)
☑ Spread Rate (ROS)
☐ Flame Length(FML)
☐ Heat / Unit Area (HPA)
☐ Crown Fire Activity (CFR)
☐ Horizontal Movement Rate (RHM)
☑ Max Spread Direction
☐ Elliptical Dimension 'a'
☐ Elliptical Dimension 'b'
☐ Elliptical Dimension 'c'
☐ Midflame Windspeed

Non-Fixed Fuel Moisture Outputs
☐ Solar Irradiance (SLR)
☐ 1hr Fuel Moisture (FM0)
☐ 10hr Fuel Moisture (FMT)

Options
● Relative Spread Direction From Maximum
○ Absolute Spread Direction Azimuth
Degrees: 0

Inputs OK
2 outputs selected
Existing outputs out of date

Once all the parameters for the run have been defined hit the apply button and then the launch button. Once the program is finished running take a look at the results. Double click on each of the two results in the right-hand pane to make sure they are in the correct units (degrees for MSD and meters per minute for ROS). Oddly enough the MSD legend is often displayed in radians (1-6) even though the units indicate degrees. After the MSD data has been exported you can open it in a text editor to ensure it is in the correct units. If you see values greater than six you should be ok. You should only need to perform the unit verification once. To export these files, right click on the ROS and MSD results and save them as .asc files. The outputs need to be named exactly as follows:

Max Spread Direction: maxdir_<dir><ptile>.asc where <dir> is wind direction (n, ne, e, se, s, sw, w, or nw) and ptile is the upper end of the percentile weather category. For the above example the file name would be: maxdir_n15.asc

Rate of Spread: ros<ptile><dir><time>.asc where time is the end time of the fuel conditioning period (either 2pm or 4am) For the above example the file name would be: ros15n2pm.asc

You will need to repeat the FlamMap runs for each of the following eight wind direction azimuths: North = 0 (done), Northeast = 45, East = 90, Southeast = 135, South = 180, Southwest = 225, West = 270 and Northwest = 315.

Once the 2pm runs are finished you will need to make the 4am runs for the same eight wind directions. Simply change the end time for the fuel conditioning period to 4am (0400), uncheck the Max Spread Direction box under outputs and make the runs for each of the same eight wind directions.

At this point you should have 16 ROS files and 8 MSD files. Create a new run with the appropriate settings and files for each of your remaining percentile weather categories.

It is a good idea to import a couple ROS files as Grids and check the max values in order to verify that they are in meters per min. As mentioned above, you should check the MSD files by opening them with a text editor to make sure they are in degrees and not radians.

The Horizontal Factor (HF) Adjustment

FlamMap calculates ROS for the direction of maximum spread (heading direction), but fire travels in other directions (backing and flanking) at lesser rates of spread as well. BurnPro needs information on ROS to find the quickest or shortest path for fire spread but this path may not always be in the direction of maximum spread. Therefore, we need to determine these rates of spread in other directions--this is where the maximum spread direction (MSD) outputs come into play. We use this FlamMap output along with a table of horizontal relative moving angles (HRMA) to estimate these lesser rates of spread. The magnitude of the adjustment is largely dependent on wind speed. Our next step is to create a

HRMA table for each of our percentile weather categories. The HRMA table is contained in a simple text file of which this is an example:

Table 5. HRMA adjustment factors.

HRMA (in degrees)	HF
0	1.00
45	1.25
90	1.50
135	1.75
180	2.00

An alternative approach to calculating ROS in non-maximum directions of travel would be to have FlamMap output ROS in each of the eight carinal directions for each combination of wind direction, percentile weather condition and two times of day. This would have necessitated 512 FlamMap runs versus the 64 currently calculated, greatly increasing the amount of labor involved in the data preparation. In addition, BurnPro's already lengthy processing time would be increased by a factor of eight. The HRMA approach is a compromise between accuracy and processing time.

BurnPro converts ROS into time by taking the inverse of ROS. For example, if you have a ROS of 0.5 meters per minute the inverse would be 1 ÷ 0.5 m/min or 2.0 minutes per meter. In other words it takes 2.0 minutes for fire to travel one meter in that cell. As mentioned above, this rate of spread applies to the direction of maximum spread. To determine how quickly fire travels in other directions we multiply it by the horizontal factor. Returning to the example in the HRMA table above, an HRMA of zero indicates the direction of maximum travel and means that the time it takes to travel a meter equals 2.0 min/m * a HF of 1.00 or 2.0 min/m. If BurnPro wants to know how fast fire travels at a right angle (90 degree HRMA) to the maximum spread direction it would multiply 2.0 min/m * 1.5 (HF) which equals 3.0 min/m and in the opposite direction of the maximum spread: 2.0 min/m * 2.00 = 4.0 min/m. To help clarify the point here is a table of the time it takes to travel a meter for various directions when the ROS is 0.5 meters per minute (time = 2.0 minutes per meter) and direction of maximum spread is due North (0 degrees):

Table 6. HRMA adjustment factor application

Direction	HRMA	HF	Time (min)
North	0	1.00	2.0
Northeast	45	1.25	2.5

East	90	1.50	3.0
Southeast	135	1.75	3.5
South	180	2.00	4.0
Southwest	135	1.75	3.5
West	90	1.50	3.0
Northwest	45	1.25	2.5

Horizontal factor varies in magnitude with wind speed and slope (Anderson, 1983 and Fons, 1946). The greater the wind speeds the larger the horizontal factors. Therefore, BurnPro requires a separate HRMA table for each of your percentile weather categories because the wind speeds vary with percentile weather category. (Note: The average wind speed you calculated for each percentile weather category are 20 foot wind speeds) An Excel spread sheet has been provided to calculate the horizontal factors for you. The following (Table 7) is an example of those calculations (low weather percentile category average wind speed = 4 mph, moderate = 6 mph, high = 10 and extreme = 15) taken directly from that spreadsheet.

Table 7. Horizontal factor calculation.

For 20' Wind speeds between 0 and 7.33 mph:

20' Wind	*M-F Wind*	*HF 45*	*HF 90*	*HF 135*	*HF 180*
4	1.2	1.337	1.720	1.976	2.118
6	1.8	1.506	2.080	2.463	2.676
	0	0.000	0.000	0.000	0.000

For 20' Wind speeds between 7.33 and 14.33 mph:

20' Wind	*M-F Wind*	*HF 45*	*HF 90*	*HF 135*	*HF 180*
10	3	1.792	2.657	3.293	3.635
	0	0.000	0.000	0.000	0.000

For 20' Wind speeds between 14.33 and 21.33 mph:

20' Wind	*M-F Wind*	*HF 45*	*HF 90*	*HF 135*	*HF 180*
15	4.5	2.147	3.364	4.333	4.821
	0	0.000	0.000	0.000	0.000

M-F wind stands for mid-flame wind speed and is calculated from a standard ratio between 20' and mid-flame wind speeds. Create one HRMA table for each percentile weather category. Be sure to use the correct section of the worksheet depending on the 20-foot wind speed you are entering (e.g. a wind speed of 10 mph goes into the "For 20' Wind speeds between 7.33 and 14.33 mph" section). Use a text editor such as notepad to create the HRMA tables. So for the low category (4 mph winds) the HRMA text file should contain the following and nothing else:

Table 8. HRMA text file example.

```
0        1.000
45       1.337
90       1.720
135      1.976
180      2.118
```

It is important that you name these files exactly as follows: hrma<ptile>.tbl. Where ptile is the upper end of the percentile category. E.g. 'hrma80.tbl' and 'hrma100.tbl'

BurnPro

Now you are ready to actually run BurnPro!

Running BurnPro

BurnPro is an ArcInfo AML (Arc Macro Language) program that requires the use of ArcInfo Grid functions and therefore must be run from a Grid prompt. Make sure you have the following files, grids, coverages and data:

- Application files: Burnpro10.aml, burnpro10_1.menu, burnpro10_2.menu and makedens.menu
- One ignition point coverage for each month in the fire season.
- Rate of Spread ASCII files (if you are using four percentile weather categories there should be 64 of these)
- Maximum Spread Direction ASCII files (if you are using four percentile weather categories there should be 32 of these)
- Elevation grid
- One HRMA file for each percentile weather category
- Remap tables: Maxrosdir.rmt, Sigma.rmt, Eta.rmt

- The fire-stopping event probabilities (one per month).
- Wind direction distributions (eight wind directions)

Tip:

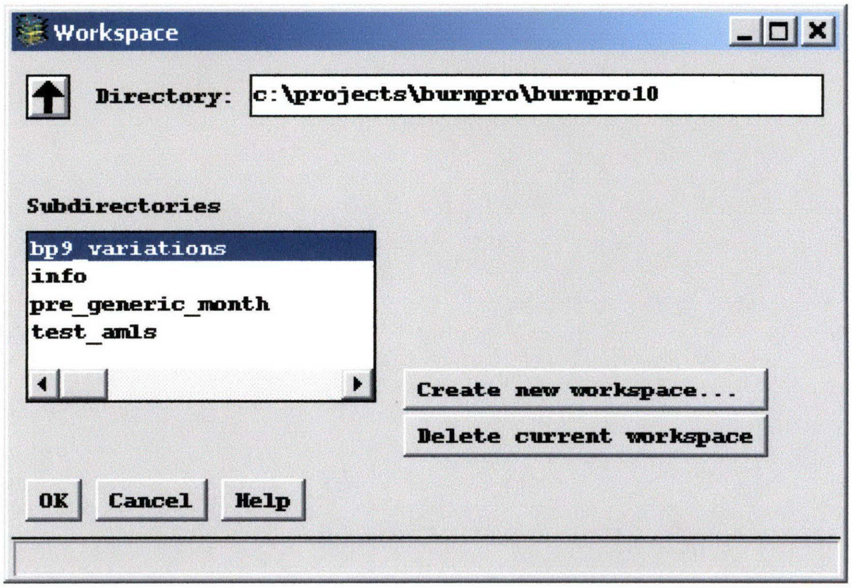
It is a good idea to reboot your computer immediately before running BurnPro.

BurnPro can take a very long time to run for large data sets. The biggest influences on run-time are the number of percentile weather categories, the size of the study area in terms of the number of cells in your input grids and the number of ignitions in the monthly ignition grids. Checking the number of rows and columns in your elevation grid will give you some idea of how long the process will take. An area with grid size 1700 X 1300 (90 meter cells) and approximately 2500 ignitions required about 24 hours to run on a 2.0 GHz Pentium 4 with 1 Gb RAM. An area with 800 X 1300 cells and 1700 ignitions required 8 hours. An area with 600 X 800 cells and 34 ignitions required 3 hours.

The BurnPro AML and menu files must be located in the same workspace. The remaining data should also be located in a common workspace but it can (and should) be a different workspace than the program files. Once you have all the necessary data located in a single workspace, start ArcInfo, navigate to the workspace where burnpro10.aml is located, start Grid and type &r burnpro10.

The first menu you encounter will be this:

Figure 11. BurnPro workspace menu.


Workspace
OK
Cancel
Help
Create new workspace...
Delete current workspace

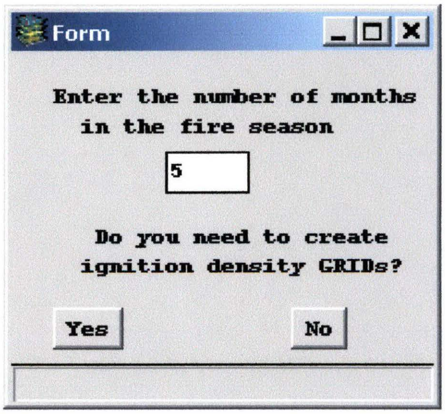
Directory: c:\projects\burnpro\burnpro10

Subdirectories

- bp9_variations
- info
- pre_generic_month
- test_amls

Use it to navigate to where your input data is located (note: your workspace should already be created and populated with all the necessary data. Therefore you shouldn't be creating new workspaces with this menu). Once you do this BurnPro will ask you for the number of months in the fire season and if you need to create ignition density grids:

Figure 12. BurnPro input menu 1.



Enter the number of months in the fire season

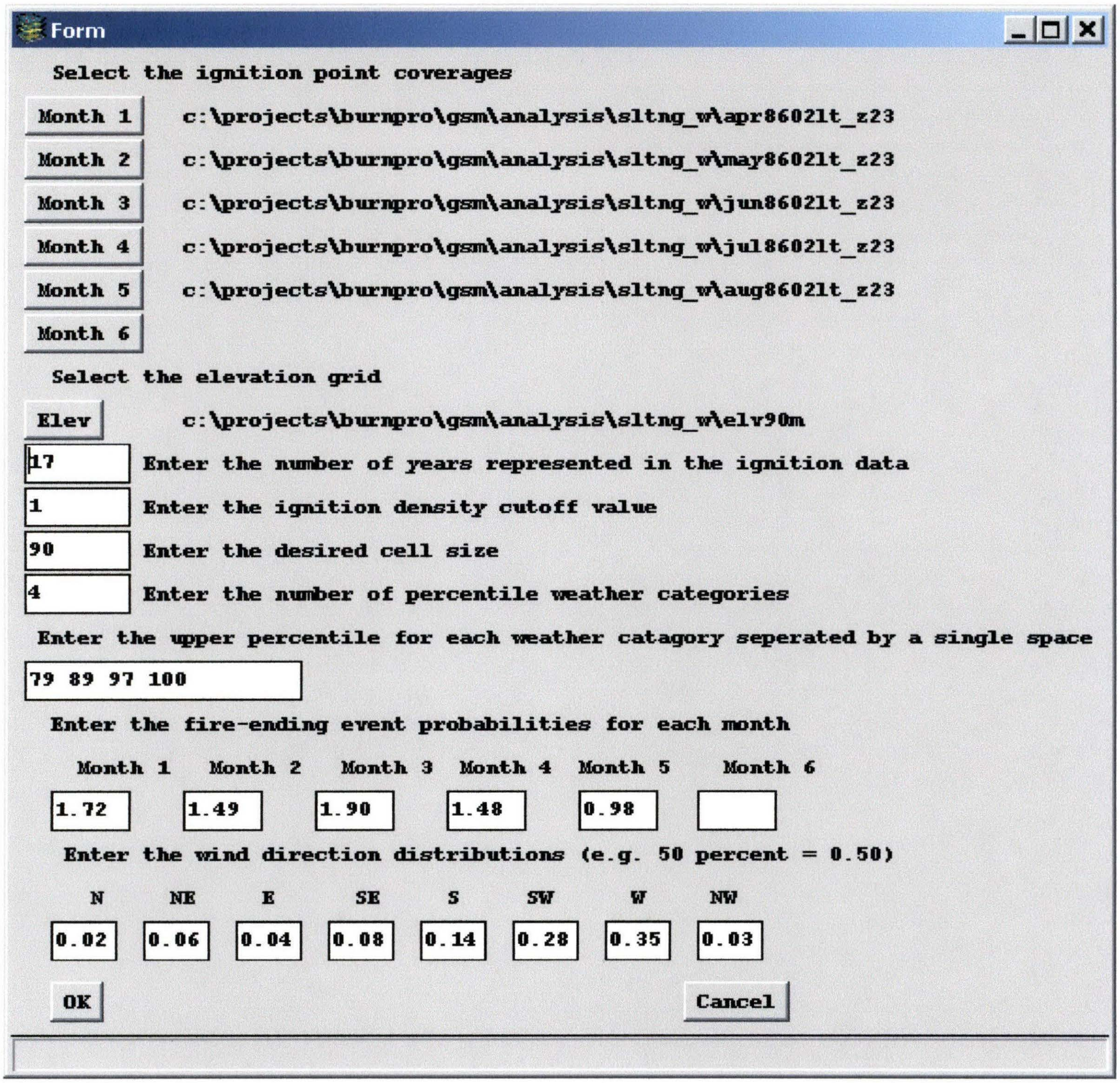
5

Do you need to create ignition density GRIDs?

Enter the number of months and choose 'Yes' for the density grid question.

At this point the following screen should appear.

Figure 13. BurnPro input menu 2.



Select the ignition point coverages

Month 1 c:\projects\burnpro\gsm\analysis\sltng_w\apr86021t_z23

Month 2 c:\projects\burnpro\gsm\analysis\sltng_w\may86021t_z23

Month 3 c:\projects\burnpro\gsm\analysis\sltng_w\jun86021t_z23

Month 4 c:\projects\burnpro\gsm\analysis\sltng_w\jul86021t_z23

Month 5 c:\projects\burnpro\gsm\analysis\sltng_w\aug86021t_z23

Month 6

Select the elevation grid

Elev c:\projects\burnpro\gsm\analysis\sltng_w\elv90m

17 Enter the number of years represented in the ignition data

1 Enter the ignition density cutoff value

90 Enter the desired cell size

4 Enter the number of percentile weather categories

Enter the upper percentile for each weather catagory seperated by a single space

79 89 97 100

Enter the fire-ending event probabilities for each month

Month 1	Month 2	Month 3	Month 4	Month 5	Month 6
1.72	1.49	1.90	1.48	0.98	

Enter the wind direction distributions (e.g. 50 percent = 0.50)

N	NE	E	SE	S	SW	W	NW
0.02	0.06	0.04	0.08	0.14	0.28	0.35	0.03

Note: Due to an odd glitch it is necessary to populate the text boxes before selecting the ignition point coverages or the elevation grid.

- Enter the number of years you used in your ignition data.
- Always enter “1” for the cutoff value.
- Enter your desired cellsize. BurnPro will resample any grids not in this cell size (including the ROS and MSD data which will be imported as grids from the ASCII files). It is a very good idea to already have your data in the desired cellsize, as this process can take a lot of time. This includes all the fuels and topography data you used to create the landscape file for FlamMap.

- Enter the number of percentile weather categories (e.g. 4)
- Enter the upper percentile for each weather category (e.g. 79 89 97 100) The last value will always be 100.
- Enter the fire-stopping event probabilities you calculated above in chronological sequence (e.g. Month 1 = May, Month 2 = June, Month 3 = July, etc.).
- Enter the wind direction distributions (e.g. 50% = 0.50)
- Select your ignition grids in chronological order using the 'Month X' buttons
- Select your elevation grid using the 'Elev' button.
- Verify all your entries.
- Hit ok and go have a sandwich… or a nap… or a weekend…

BurnPro Results

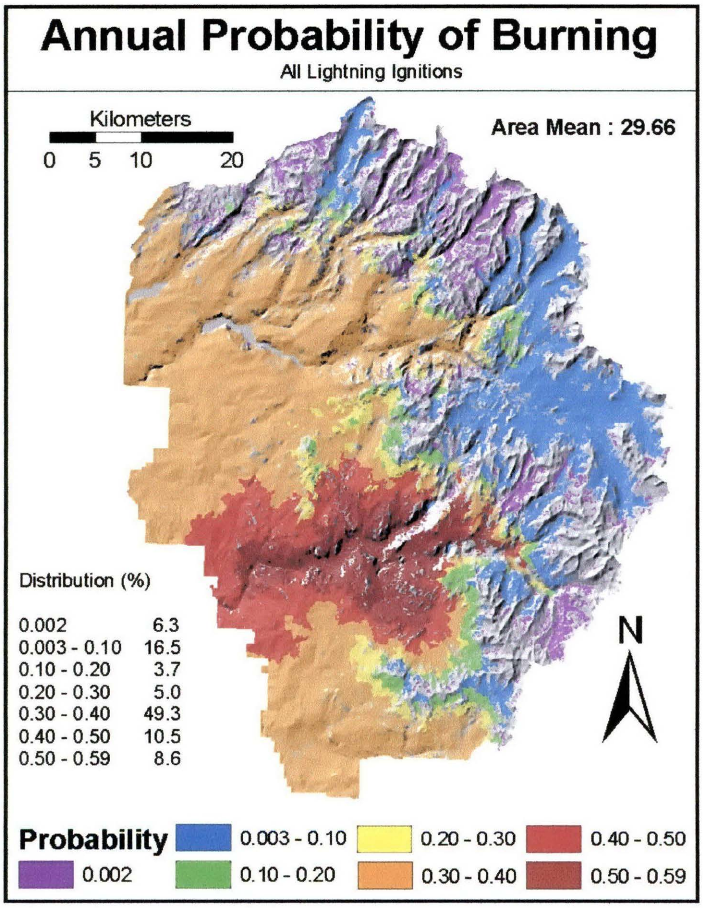
BurnPro outputs the following ArcInfo grids:

- avgall – this is the main output. It contains the average annual probability of burning values for your study area.
- avg_<ptile> - these grids contain the probability of burning under the percentile weather category for which they are named. E.g. if your categories are 0-79, 80-89, 90-97 and 98-100 then avg_100 would contain the probability of burning for the 98-100 category, avg_97 the probability of burning for the 90-97 category etc.
- avg_<dir> – these grids contain the probability of burning for a particular wind direction and are named accordingly (e.g.North-avg_n, Northeast-avg_ne etc.)

Interpreting BurnPro Results

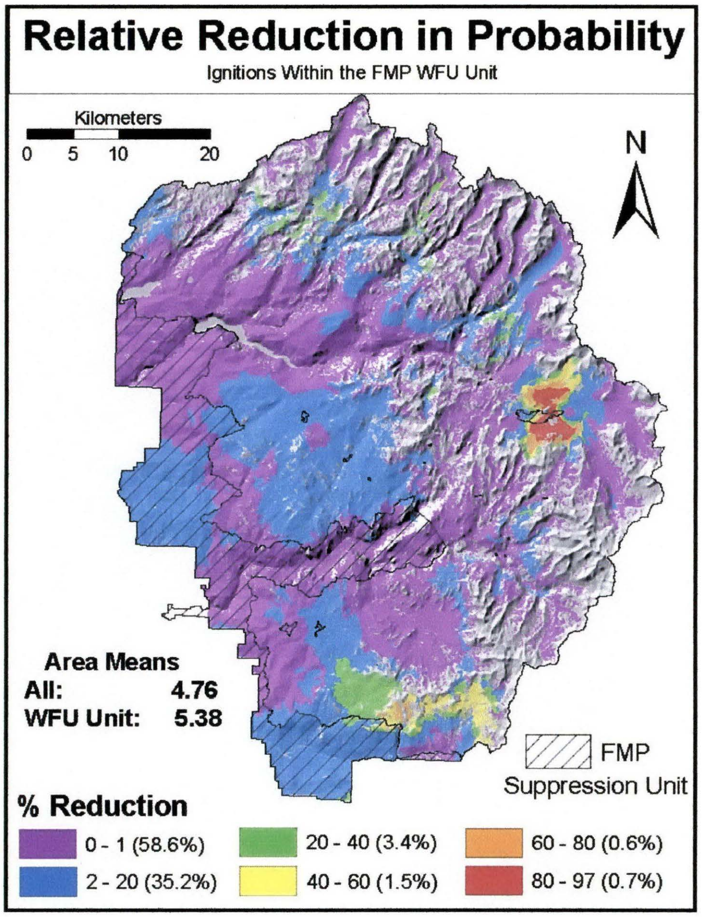
The values in BurnPro's output grids represent average annual probability of burning. The probability of any event can range from 0 (certain it won't occur) to 1 (certain it will occur). The numbers output by BurnPro have been converted to percentages and will range from 0.2 to 100%. It is important that these values be interpreted as *relative* probabilities rather than as absolute probabilities. A value of 20% should not be interpreted as having a one-in-five chance of occurring, but it can be interpreted as being twice as likely as a value 10%. The predictions are based on long-term ignition and weather patterns and therefore should be used for long-term planning efforts rather than being interpreted for short-term purposes. Below is an example of the average annual probability of burning for Yosemite National Park (Figure 14).

Figure 14. Annual probability of burning example.


Annual Probability of Burning
All Lightning Ignitions
Kilometers
0 5 10 20
Area Mean : 29.66
Distribution (%)
0.002 6.3
0.003 - 0.10 16.5
0.10 - 0.20 3.7
0.20 - 0.30 5.0
0.30 - 0.40 49.3
0.40 - 0.50 10.5
0.50 - 0.59 8.6
N
Probability
0.002
0.003 - 0.10
0.10 - 0.20
0.20 - 0.30
0.30 - 0.40
0.40 - 0.50
0.50 - 0.59

Where current conditions allow for WFU, results can be evaluated to see if there are sufficient natural ignitions to restore natural fire frequencies. This will help to identify those areas where restoration objectives can be most easily met through the use of natural ignitions; these areas could be given priority for implementing WFU programs (See Figure 15).

Figure 15. Relative reduction in probability of burning example.


Relative Reduction in Probability
Ignitions Within the FMP WFU Unit
Kilometers
0 5 10 20
N
Area Means
All: 4.76
WFU Unit: 5.38
FMP Suppression Unit
% Reduction
0 - 1 (58.6%)
2 - 20 (35.2%)
20 - 40 (3.4%)
40 - 60 (1.5%)
60 - 80 (0.6%)
80 - 97 (0.7%)

This information is also useful in helping to identify areas within candidate WFU zones where the number, location, and timing of natural ignitions are inadequate for restoring fire. In these areas, the use of prescribed fire, or even accidental human-caused ignitions, could be evaluated in light of restoration objectives.

General Caveats

Any model is merely a simulation of reality and will never be completely accurate. BurnPro is certainly no exception. The following are a few of the caveats to keep in mind when interpreting BurnPro's results.

1. BurnPro's predictions are only as good as the accuracy of the input data. The better (more accurate, longer periods of record etc.) the input data the more accurate the predictions.

2. BurnPro's predictions are based on current fuels. If there is a change in the fuels (e.g. via a fire) predictions will change. What this means is that BurnPro's predictions remain accurate only so long as the underlying data remains the same.

3. The ignition density grids BurnPro uses are developed from the monthly ignition point coverages using the ArcInfo command POINTSTATS. In our implementation, pointstats merely counts the number of points within a particular radius of a grid cell and populates the cell with this data. We then divide this number by the number of years represented by the ignition data to obtain an annual ignition density. We used a search radius of 564.19 meters. This radius was chosen because it results in a search *area* of one square kilometer. The selection of this search radius was a compromise between the following factors: locational inaccuracy of the reported ignition points, short periods of record for ignition data (and therefore low densities) and the minimization of the misleading data generated by large search radii. But, the choice of this particular search radius could be seen as being somewhat arbitrary.

4. HRMAs are calculated based on data developed on flat ground (Anderson, 1983; Fons, 1946), and therefore do not take wind-slope interactions into account.

5. ROS are based on daily averages between ROS at 4am and 2pm. Therefore, the impacts of weather variability at shorter time scales (e.g. a 2 hour wind

event) are not represented by the model. In addition, investigations comparing twice-daily averages to twelve-times-daily averages indicate that twice-daily may slightly over-predict ROS.

6. Probability predictions near the edge of the study area are less accurate than those further in. This is because predictions near the edge don't account for the influence of fires immigrating in from outside the study area.

7. Keep in mind the fact that BurnPro's predictions don't account for any suppression efforts.

8. Weather data is gathered from a RAWS station at a single point (or at a few points if using multiple RAWS) but is applied to a much wider area. Variability in weather conditions over the area are not accounted for.

Appendix B Presentations

BurnPro Poster

Poster presented at 2nd International Wildland Fire Ecology and Fire Management Congress, Orlando, FL, November 2003 and National Fire Plan Conference, Reno, NV, February 2004.

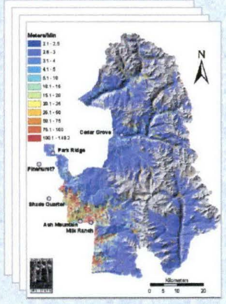
USING THE PROBABILITY OF BURNING TO PLAN FOR WILDLAND FIRE USE

CAROL MILLER, BRETT DAVIS, ANNE BLACK

ALDO LEOPOLD WILDERNESS RESEARCH INSTITUTE, USDA FOREST SERVICE ROCKY MOUNTAIN RESEARCH STATION, MISSOULA, MT

The GIS model BurnPro predicts the annual probability of burning for every pixel in a raster landscape. BurnPro uses topography, historic weather, maps of fuels, and historic ignition locations to estimate the likelihood of burning given the speed and direction a fire might burn from any ignition point, the length of the fire season, and the likelihood of fire-stopping precipitation events during the fire season. These estimates are used to assist in developing fire management plans.

RATE OF SPREAD

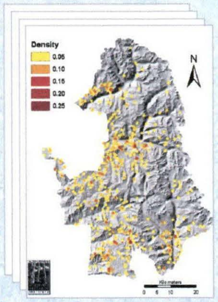


(example: extreme weather)

20 years of historic weather data were analyzed for 3 weather stations. FireFamilyPlus (Main et al. 1990) was used to compute Spread Component (SC) index; these were used to define 4 classes (low, moderate, high, and extreme) of fire weather conditions.

Expected rate of spread (ROS) was calculated using FlamMap (Fire Sciences Lab 2003) for every combination of the 4 weather classes and 8 separate wind directions. FlamMap computes potential fire behavior for every cell in a raster landscape.

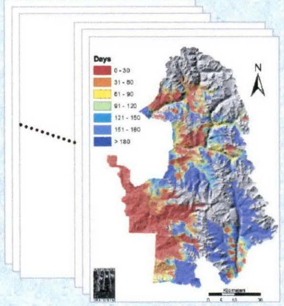
IGNITIONS



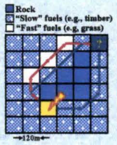
Point location data for 20 years of lightning-caused ignitions were separated into 4 months (June, July, August, and September) and then used to derive ignition density maps representing 1, 2, 3, 4, and 5+ ignitions per km² per month.

These 20 maps (4 months x 5 density classes) were used in the next step to compute the least accumulative spread time.

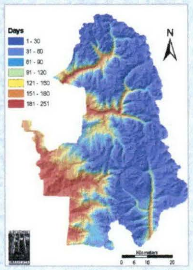
BurnPro follows logic similar to RERAP, a nonspatial model which estimates the probability that a fire will threaten a point of concern before a fire-ending event (rain) occurs (FRAMES 2003). BurnPro translates this to a spatially explicit landscape and to many possible fires that may occur over many years (Miller 2003). The probability that a pixel will burn depends on 1) the time required for fire to spread from an ignition to that pixel relative to the time remaining in the fire season, and 2) the frequency of fire-ending rain events within the fire season.



LEAST ACCUMULATIVE SPREAD TIME (T)



The inverse of ROS is the cost (in time) per unit of surface distance. ArcGIS PATHDISTANCE was used to find the least accumulative spread time from each ignition source to every cell on the landscape. The function accounts for horizontal factors like wind and slope that influence the time needed to move from cell to cell. 20 ignition grids x 4 ROS grids x 8 wind directions = 640 "T" grids



LENGTH OF FIRE SEASON (drought-days)

Fire season may range from several months at low elevations to perhaps only a few days at the highest elevations. Simulations of a drought-day index (Urban et al. 2000) were used to approximate the length of the fire season at 100-m elevation intervals across the landscape. The frequency distribution of drought-days from 100 replicate simulations for each elevation was fit to a waiting-time (Weibull) function to derive parameters α and β.

Probability of burning = Pburn1 x Pburn2

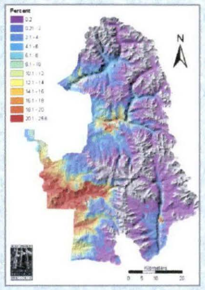
$$\text{Pburn1} = 1 - \exp\left[-\left(\frac{T}{\beta}\right)^{\alpha}\right]$$

The probability that fire will spread to each pixel on the landscape before the end of the fire season is calculated for each of the Least Accumulative Spread Time maps (T). The parameters α and β describe the variability and length of the fire season.

$$\text{Pburn2} = 1 - \text{P(significant rain)}$$

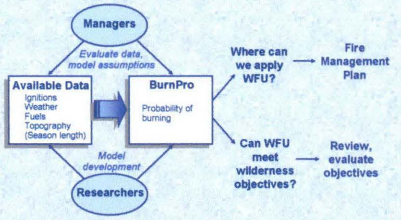
FireFamilyPlus (Main et al. 1990) was used to determine the probability that a significant rain event (at least 0.5 inches within 5 days or less; Latham and Rothermel 1993) would stop a fire before the end of the fire season. Subtracting this probability from 1 gives the probability that fires are unhindered by precipitation during the fire season.

ANNUAL PROBABILITY OF BURNING



The probability of burning grids were combined using a weighted average approach where the weights were assigned according to the frequency of occurrence (Miller 2003). The result was an average estimate of the annual probability of burning.

Estimates of probability of burning are being used to identify where wildland fire use (WFU) is feasible given the current conditions of fuels and the risks to ecological and social values. This information is also being used to evaluate if the number, location, and timing of WFU ignitions are adequate for restoring historic fire regimes in wilderness and parks.



These analyses are being conducted for 4 National Parks (Yosemite, Sequoia-Kings Canyon, Grand Canyon, and Great Smoky Mountains) and 2 Forest Service wilderness areas (Selway-Bitterroot and Gila-Aldo Leopold) to improve fire management plans and refine management objectives.

This poster is part of a Joint Fire Science Project
"Can Wildland Fire Use Restore Historical Fire Regimes?"

The Aldo Leopold Wilderness Research Institute is administered by the USFS's Rocky Mountain Research Station and operates under an agreement with the US Forest Service, Bureau of Land Management, National Park Service, US Fish and Wildlife Service, and US Geological Survey.

The goals of the Leopold Institute are to develop the knowledge needed to protect and preserve wilderness and the ecological and social derived from it, and to communicate and apply this knowledge to management agencies and other user groups. Visit our web site at http://leopold.wilderness.net

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FRAMES 2003. Fire Research and Management Exchange System, Fire Management Tools Online [Online] Available http //www frames gov/tools/#RERAP [May 3, 2003]

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Main, W.A. et al. 1990. FIREFAMILY 1988 General Technical Report NC-138, U.S. Department of Agriculture, Forest Service, North Central Forest Experiment Station, St Paul MN

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Urban, D.L. et al. 2000. Forest gradient response in Sierran landscapes the physical template. Landscape Ecology 15 603-620

Probabilty of Burning Poster

Poster presented at Mixed Severity Fire Regime Conference, Spokane, WA, November 2004.

PROBABILITY OF BURNING ANALYSES IMPROVE WILDLAND FIRE PLANNING

CAROL MILLER, BRETT DAVIS, ANNE BLACK

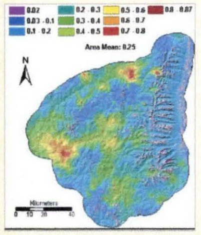
ALDO LEOPOLD WILDERNESS RESEARCH INSTITUTE, USDA FOREST SERVICE ROCKY MOUNTAIN RESEARCH STATION, MISSOULA, MT

Fire stewardship planning is improved with information about how the probability of burning varies across a landscape:

- **Where is fire most likely to burn?**
  Risk assessment, prioritization, prevention planning
- **Where are opportunities for Wildland Fire Use?**
  Fire Management Planning (FMP), go/no-go decision support
- **How will FMP affect WFU opportunities?**
  Review, evaluate objectives

Opportunities for WFU in the Selway-Bitterroot

Estimates of probability of burning can help identify areas with the greatest opportunities for WFU. This map illustrates the probability of burning from lightning-caused ignitions in the Selway-Bitterroot Wilderness.

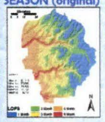

0.02
0.03 - 0.1
0.1 - 0.2
0.2 - 0.3
0.3 - 0.4
0.4 - 0.5
0.5 - 0.6
0.6 - 0.7
0.7 - 0.8
0.8 - 0.87
Area Mean: 0.25
N
Kilometers
0 10 20 40

Areas with high probability of burning indicate where WFU opportunities are relatively common or frequent. Although the preferred strategy in wilderness is WFU, fires are often suppressed due to external factors (e.g., lack of resources available to monitor the fire). In such cases, wilderness fire managers can at least expect to have another opportunity to manage for WFU relatively soon in these areas.

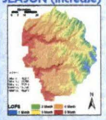
On the other hand, where probability of burning is low, WFU opportunities are relatively rare and suppression should be avoided in these areas whenever possible.

Sensitivity to Season-length Variability in Yosemite

LENGTH OF FIRE SEASON (original)



LENGTH OF FIRE SEASON (increase)



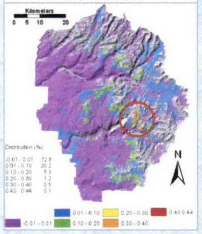
Length of the fire season varies across the landscape and from year to year. How sensitive is the probability of burning in Yosemite National Park to this variability?

We ran BurnPro using two different estimates for fire season length (left). In the second run, we increased the length of the fire season by shifting the season uphill by 500m (bottom left).

The large map to the right illustrates the difference between the 2 runs. On average, there is little change in probability of burning with a longer fire season—but note there are some places that may be highly sensitive.

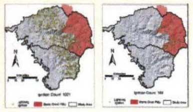
Probability of Burning Change

Increased LOFS Minus Normal LOFS


Kilometers
0 5 10 20
Distribution (%)
-0.01 - 0.01 72.8
0.01 - 0.10 20.2
0.10 - 0.20 5.3
0.20 - 0.30 1.2
0.30 - 0.40 0.5
0.40 - 0.44 0.1
N
-0.01 - 0.01
0.01 - 0.10
0.10 - 0.20
0.20 - 0.30
0.30 - 0.40
0.40 - 0.44

Challenges for Restoration in Sequoia-Kings Canyon

We used BurnPro to evaluate how suppression of lightning-caused fires on lands outside the Fire Management Unit (FMU) might affect the rate of burning within the FMU. We asked: what is the effect of eliminating the importation of these fires?


N
Ignition Count: 1001
Ignition Count: 189
Sierra Crest FMU
Study Area

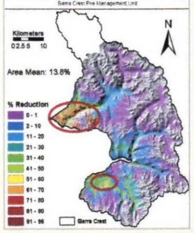
The maps to the left show the FMU in the context of the interagency planning area, and 2 ignition scenarios used to run BurnPro: 1) all lightning ignitions, and 2) only lightning ignitions that occur inside the FMU where WFU is allowed.

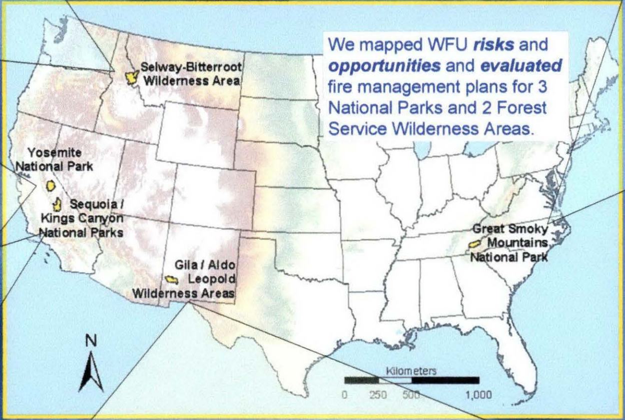
We estimated probability of burning for 2 scenarios (illustrated above). The large map to the right illustrates the difference in probability of burning in the FMU between the two scenarios.

Areas with high % reduction in the map on the right are areas where it may be especially difficult to restore fire to a natural frequency due to suppression on adjacent lands. In these areas, opportunities for WFU should be maximized and periodic prescribed burning over the long term may be warranted.

Relative Reduction in Probability

Sierra Crest Fire Management Unit


Kilometers
0 2.5 5 10
Area Mean: 13.8%
% Reduction
0 - 1
2 - 10
11 - 20
21 - 30
31 - 40
41 - 50
51 - 60
61 - 70
71 - 80
81 - 90
91 - 96
Sierra Crest
N


Selway-Bitterroot Wilderness Area
Yosemite National Park
Sequoia / Kings Canyon National Parks
Gila / Aldo Leopold Wilderness Areas
Great Smoky Mountains National Park
N
Kilometers
0 250 500 1,000

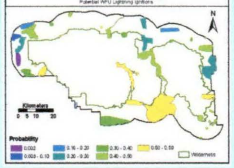
We mapped WFU ***risks*** and ***opportunities*** and ***evaluated*** fire management plans for 3 National Parks and 2 Forest Service Wilderness Areas.

Risk Assessment in the Gila-Aldo Leopold Wilderness

Estimates of probability of burning can improve risk assessments and help prioritize fuels treatments. We overlaid our estimates of probability of burning with information about two important values at risk in the Gila-Aldo Leopold Wilderness: the wildland urban interface (below, left), and Mexican spotted owl habitat (below, right). Areas containing a value-at-risk that also have a high probability of burning are given high priority for fuels treatment.

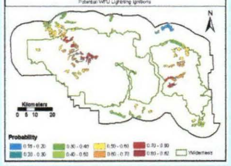
Probability of Burning WUI

Potential WFU Lightning Ignitions


N
Kilometers
0 5 10 20
Probability
0.002
0.003 - 0.10
0.16 - 0.20
0.20 - 0.30
0.30 - 0.40
0.40 - 0.50
0.50 - 0.59
Wilderness

Probability of Burning MSO Habitat

Potential WFU Lightning Ignitions


N
Kilometers
0 5 10 20
Probability
0.16 - 0.20
0.20 - 0.30
0.30 - 0.40
0.40 - 0.50
0.50 - 0.60
0.60 - 0.70
0.70 - 0.80
0.80 - 0.82
Wilderness

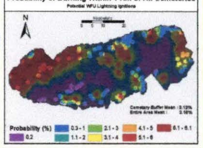
Risks and Benefits in Great Smoky Mountains

A primary goal in Great Smoky Mountains National Park is to preserve the natural processes (such as fire) that perpetuate its extraordinary plant and animal diversity. In addition, the Park is valued for its many cultural and historical resources.

We used our estimates of probability of burning to examine some of the risks and benefits that WFU may pose to these different Park values. The map on the right illustrates the probability of burning within 1km of a cemetery. The map below illustrates the probability of burning in vegetation types with pine or mixed pine overstory. These are forest types expected to benefit from WFU.

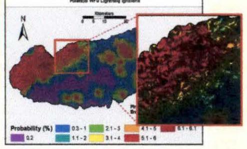
Probability of Burning Within 1 Km of All Cemeteries

Potential WFU Lightning Ignitions


N
Kilometers
0 5 10 20
Cemetery Buffer Mean: 3.12%
Entire Area Mean: 2.16%
Probability (%)
0.2
0.3 - 1
1.1 - 2
2.1 - 3
3.1 - 4
4.1 - 5
5.1 - 6
6.1 - 6.1

Probability of Burning - Pine / Mixed-Pine Overstory

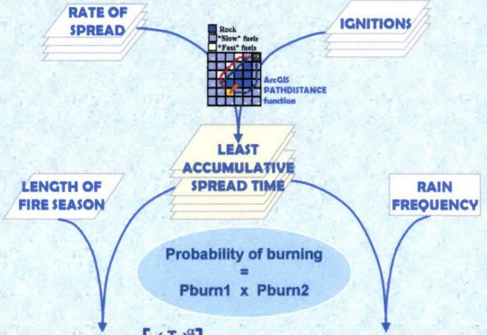
Potential WFU Lightning Ignitions


N
Kilometers
0 5 10 20
Probability (%)
0.2
0.3 - 1
1.1 - 2
2.1 - 3
3.1 - 4
4.1 - 5
5.1 - 6
6.1 - 6.1

We found that most of the Park has a very low probability of burning, with few opportunities for WFU. Fire management staff are using this finding to justify and support their prescribed fire program.

Overview of BurnPro:

The GIS model BurnPro predicts the annual probability of burning for every pixel in a raster landscape. BurnPro uses topography, historic weather, fuels maps, and historic ignition locations to estimate the likelihood of burning given the speed and direction a fire might burn from any ignition point, the length of the fire season, and the frequency of fire-stopping rain events during the fire season.


RATE OF SPREAD
IGNITIONS
Rock
"Slow" fuels
"Fast" fuels
ArcGIS PATHDISTANCE function
LEAST ACCUMULATIVE SPREAD TIME
LENGTH OF FIRE SEASON
RAIN FREQUENCY

Probability of burning = Pburn1 x Pburn2

$$\text{Pburn1} = 1 - \exp\left[-\left(\frac{T}{\beta}\right)^{\alpha}\right]$$

The probability that fire will spread to each pixel on the landscape before the end of the fire season is calculated for each of the Least Accumulative Spread Time maps (T).

$$\text{Pburn2} = 1 - P(\text{significant rain})$$

The probability that fire will reach each pixel before a significant rain event occurs is calculated from the Least Accumulative Spread Time and the frequency of fire-stopping rain events.

ALDO LEOPOLD WILDERNESS RESEARCH INSTITUTE

The goals of the Leopold Institute are to develop the knowledge needed to protect and preserve wilderness and the ecological and social values derived from it, and to communicate and apply this knowledge to management agencies and other user groups. Visit our web site at http://leopold.wilderness.net

USGS

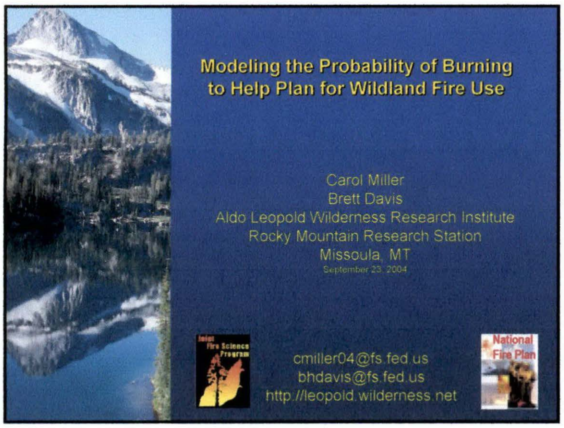
Joint Fire Science Program

National Fire Plan

This research was supported by the Joint Fire Science Program and the National Fire Plan

Symposium on Science and Monitoring

Modeling the probability of burning to help plan for wildland fire use. Presented at Symposium on Science and Monitoring, Denver, CO, September 2004.



Modeling the Probability of Burning to Help Plan for Wildland Fire Use

Carol Miller
Brett Davis
Aldo Leopold Wilderness Research Institute
Rocky Mountain Research Station
Missoula, MT
September 23, 2004

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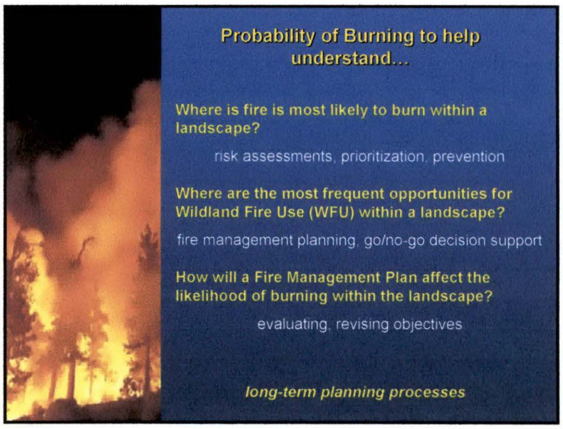
Joint Fire Science Program
National Fire Plan



Probability of Burning to help understand...

Where is fire is most likely to burn within a landscape?

risk assessments, prioritization, prevention

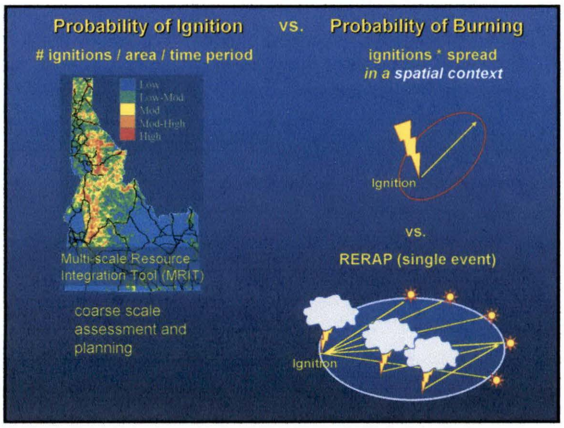
Where are the most frequent opportunities for Wildland Fire Use (WFU) within a landscape?

fire management planning, go/no-go decision support

How will a Fire Management Plan affect the likelihood of burning within the landscape?

evaluating, revising objectives

long-term planning processes



Probability of Ignition vs. Probability of Burning

# ignitions / area / time period

Low
Low-Mod
Mod
Mod-High
High

Multi-scale Resource Integration Tool (MRIT)

coarse scale assessment and planning

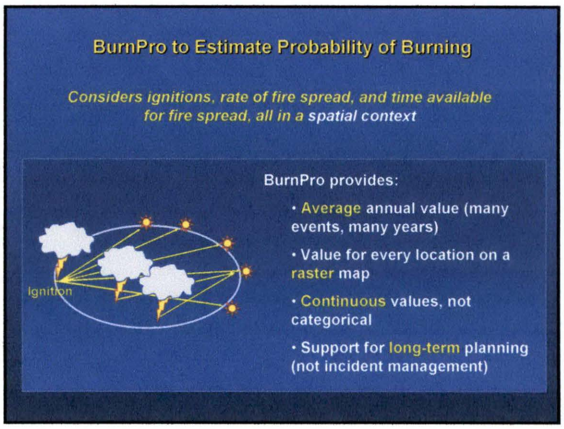
ignitions * spread
in a spatial context

Ignition

vs.

RERAP (single event)

Ignition

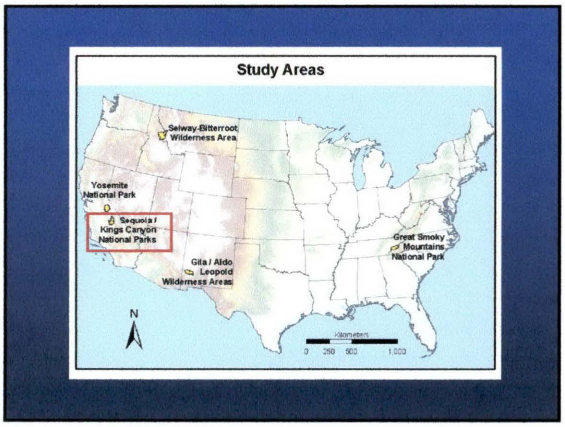


BurnPro to Estimate Probability of Burning

Considers ignitions, rate of fire spread, and time available for fire spread, all in a spatial context

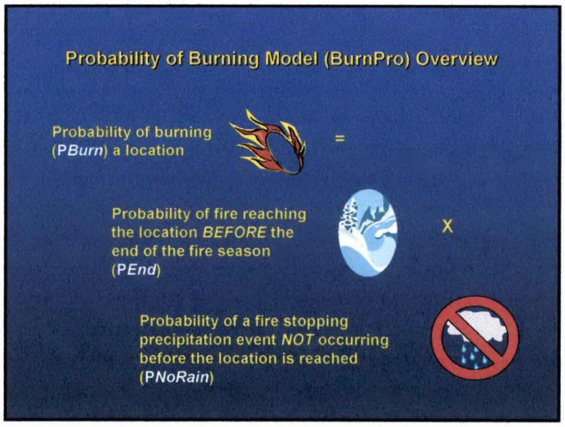
BurnPro provides:

- Average annual value (many events, many years)
- Value for every location on a raster map
- Continuous values, not categorical
- Support for long-term planning (not incident management)



Study Areas

Selway-Bitterroot Wilderness Area
Yosemite National Park
Sequoia / Kings Canyon National Parks
Gila / Aldo Leopold Wilderness Areas
Great Smoky Mountains National Park
N
Kilometers
0 250 500 1,000

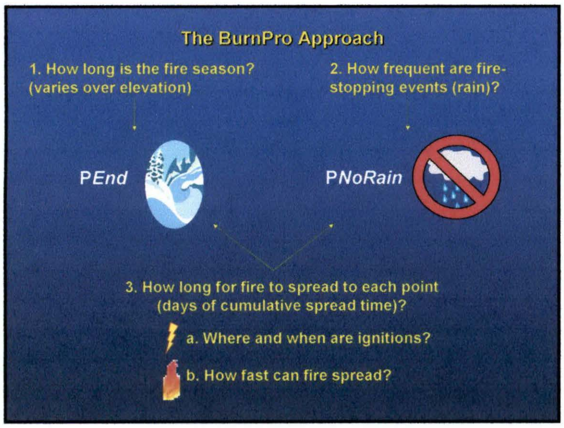


Probability of Burning Model (BurnPro) Overview

Probability of burning (*PBurn*) a location =

Probability of fire reaching the location *BEFORE* the end of the fire season (*PEnd*) X

Probability of a fire stopping precipitation event *NOT* occurring before the location is reached (*PNoRain*)



The BurnPro Approach

1. How long is the fire season? (varies over elevation)

2. How frequent are fire-stopping events (rain)?

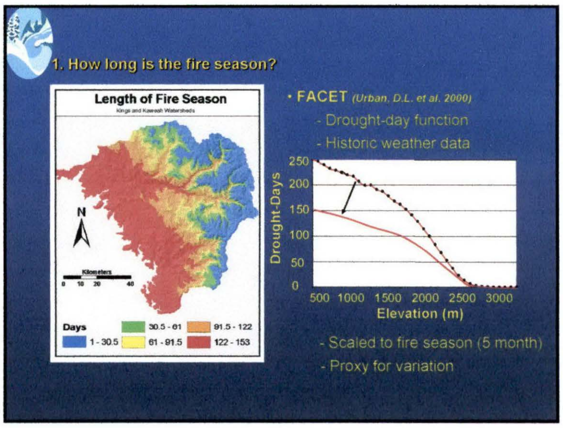
PEnd

PNoRain

3. How long for fire to spread to each point (days of cumulative spread time)?

a. Where and when are ignitions?

b. How fast can fire spread?



1. How long is the fire season?

Length of Fire Season

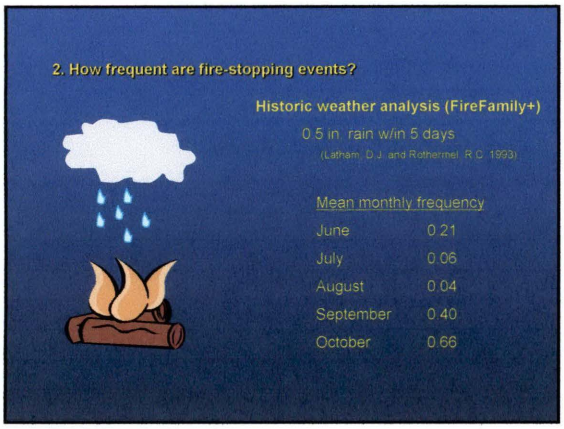
Kings and Kaweah Watersheds

N
Kilometers
0 10 20 40
Days
1 - 30.5
30.5 - 61
61 - 91.5
91.5 - 122
122 - 153

- FACET *(Urban, D.L. et al. 2000)*
  - Drought-day function
  - Historic weather data

Drought-Days
250
200
150
100
50
0
500 1000 1500 2000 2500 3000
Elevation (m)

- Scaled to fire season (5 month)
- Proxy for variation



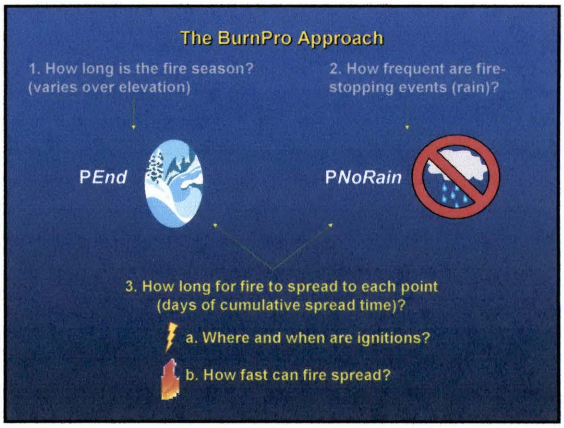
2. How frequent are fire-stopping events?

Historic weather analysis (FireFamily+)

0.5 in. rain w/in 5 days

(Latham, D.J. and Rothermel, R.C. 1993)

Mean monthly frequency	
June	0.21
July	0.06
August	0.04
September	0.40
October	0.66



The BurnPro Approach

1. How long is the fire season? (varies over elevation)

2. How frequent are fire-stopping events (rain)?

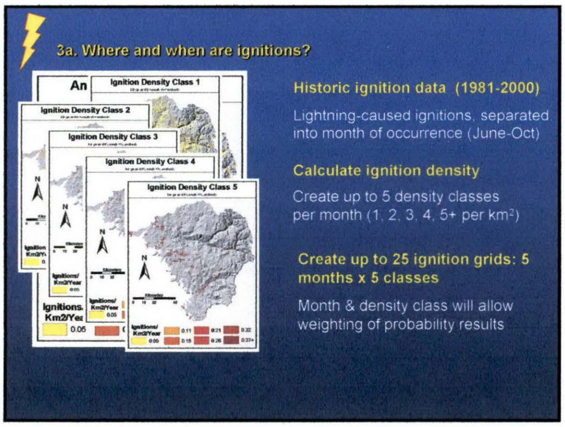
PEnd

PNoRain

3. How long for fire to spread to each point (days of cumulative spread time)?

a. Where and when are ignitions?

b. How fast can fire spread?



3a. Where and when are ignitions?

An
Ignition Density Class 1
Ignition Density Class 2
Ignition Density Class 3
Ignition Density Class 4
Ignition Density Class 5
N
Ignitions/ Km2/Year
0.05
0.11
0.16
0.21
0.26
0.32
0.37+

Historic ignition data (1981-2000)

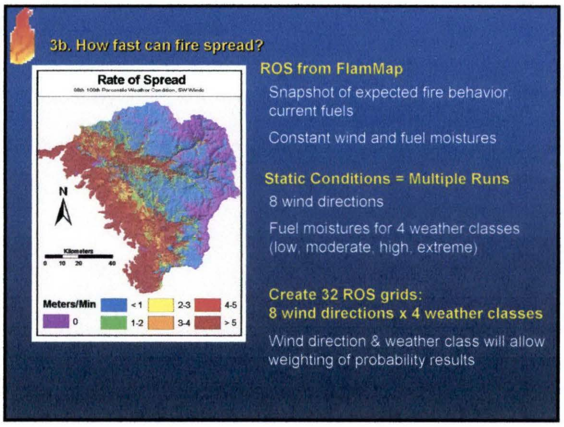
Lightning-caused ignitions, separated into month of occurrence (June-Oct)

Calculate ignition density

Create up to 5 density classes per month (1, 2, 3, 4, 5+ per km^2)

Create up to 25 ignition grids: 5 months x 5 classes

Month & density class will allow weighting of probability results



3b. How fast can fire spread?

Rate of Spread

N
Kilometers
0 10 20 40
Meters/Min
0
< 1
1-2
2-3
3-4
4-5
> 5

ROS from FlamMap

Snapshot of expected fire behavior, current fuels

Constant wind and fuel moistures

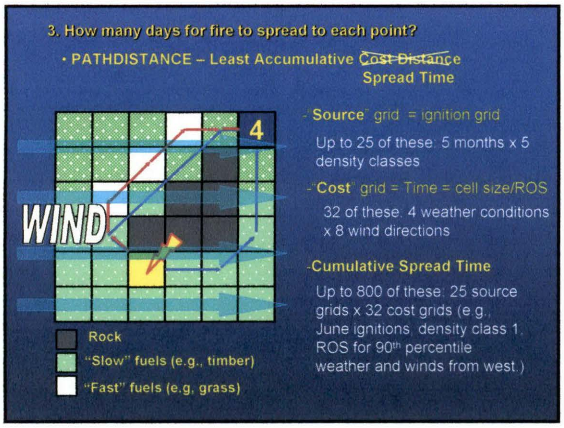
Static Conditions = Multiple Runs

8 wind directions

Fuel moistures for 4 weather classes (low, moderate, high, extreme)

Create 32 ROS grids: 8 wind directions x 4 weather classes

Wind direction & weather class will allow weighting of probability results



3. How many days for fire to spread to each point?

- PATHDISTANCE – Least Accumulative ~~Cost Distance~~ Spread Time

-"Source" grid = ignition grid

Up to 25 of these: 5 months x 5 density classes

-"Cost" grid = Time = cell size/ROS

32 of these: 4 weather conditions x 8 wind directions

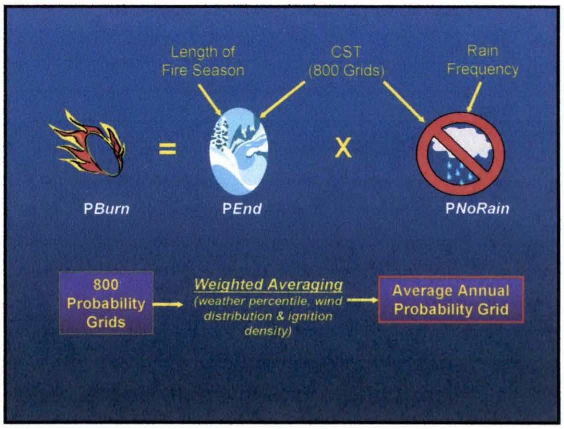
-Cumulative Spread Time

Up to 800 of these: 25 source grids x 32 cost grids (e.g., June ignitions, density class 1, ROS for 90th percentile weather and winds from west.)

■ Rock

🟩 "Slow" fuels (e.g., timber)

☐ "Fast" fuels (e.g, grass)



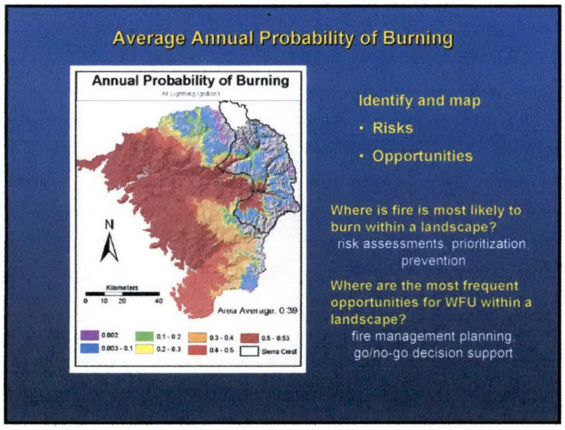
Length of Fire Season

CST (800 Grids)

Rain Frequency

P*Burn* = P*End* X P*NoRain*

800 Probability Grids → ***Weighted Averaging*** *(weather percentile, wind distribution & ignition density)* → Average Annual Probability Grid



Average Annual Probability of Burning

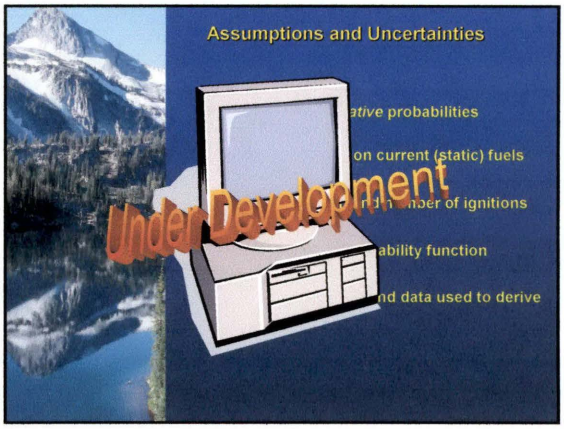
Annual Probability of Burning
All Lightning Ignitions
N
Kilometers
0 10 20 40
Area Average: 0.39
0.002
0.003 - 0.1
0.1 - 0.2
0.2 - 0.3
0.3 - 0.4
0.4 - 0.5
0.5 - 0.53
Sierra Crest

Identify and map

- Risks
- Opportunities

Where is fire is most likely to burn within a landscape?
risk assessments, prioritization, prevention

Where are the most frequent opportunities for WFU within a landscape?
fire management planning, go/no-go decision support



Assumptions and Uncertainties

Under Development

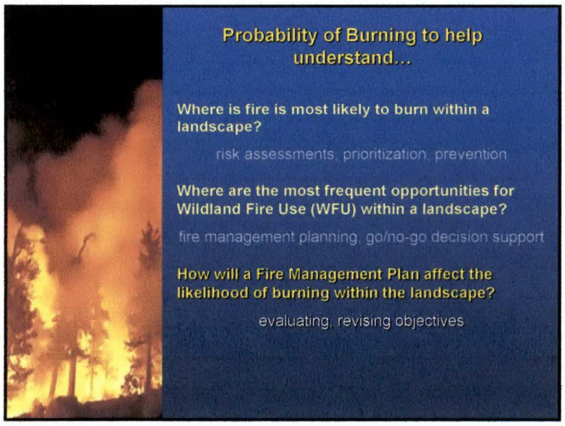
ative probabilities

on current (static) fuels

n[illegible]ber of ignitions

ability function

nd data used to derive



Probability of Burning to help understand…

Where is fire is most likely to burn within a landscape?

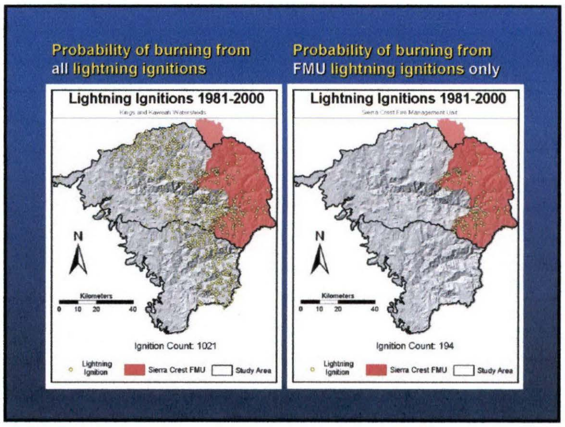
risk assessments, prioritization, prevention

Where are the most frequent opportunities for Wildland Fire Use (WFU) within a landscape?

fire management planning, go/no-go decision support

How will a Fire Management Plan affect the likelihood of burning within the landscape?

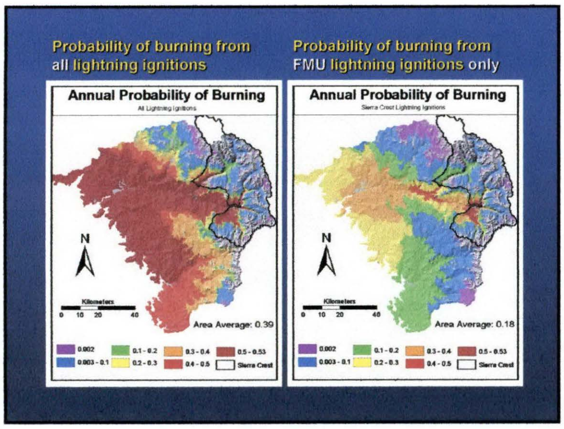
evaluating, revising objectives



Probability of burning from all lightning ignitions

Probability of burning from FMU lightning ignitions only

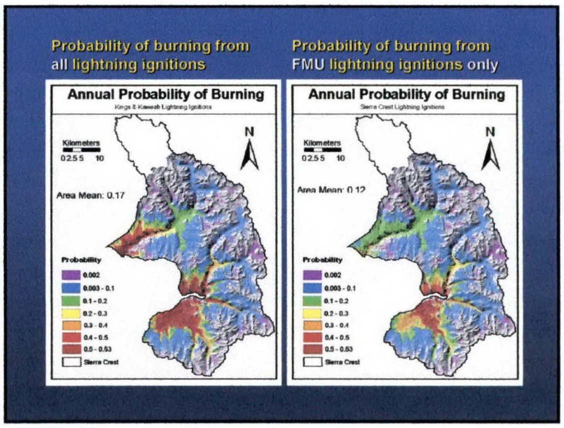
Lightning Ignitions 1981-2000
Kings and Kaweah Watersheds
N
Kilometers
0 10 20 40
Ignition Count: 1021
Lightning Ignition
Sierra Crest FMU
Study Area
Lightning Ignitions 1981-2000
Sierra Crest Fire Management Unit
N
Kilometers
0 10 20 40
Ignition Count: 194
Lightning Ignition
Sierra Crest FMU
Study Area



Probability of burning from all lightning ignitions

Probability of burning from FMU lightning ignitions only

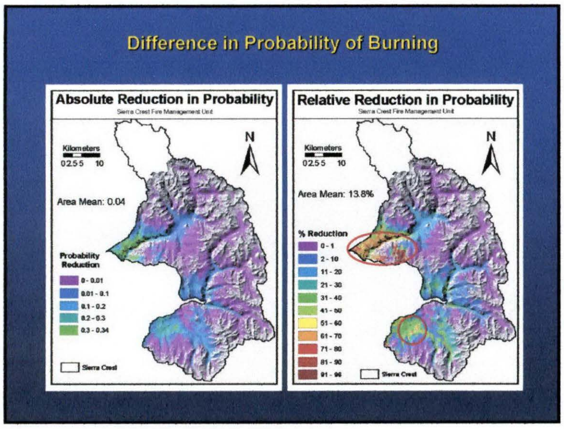
Annual Probability of Burning
All Lightning Ignitions
N
Kilometers
0 10 20 40
Area Average: 0.39
0.002
0.003 - 0.1
0.1 - 0.2
0.2 - 0.3
0.3 - 0.4
0.4 - 0.5
0.5 - 0.53
Sierra Crest
Annual Probability of Burning
Sierra Crest Lightning Ignitions
N
Kilometers
0 10 20 40
Area Average: 0.18
0.002
0.003 - 0.1
0.1 - 0.2
0.2 - 0.3
0.3 - 0.4
0.4 - 0.5
0.5 - 0.53
Sierra Crest



Probability of burning from all lightning ignitions

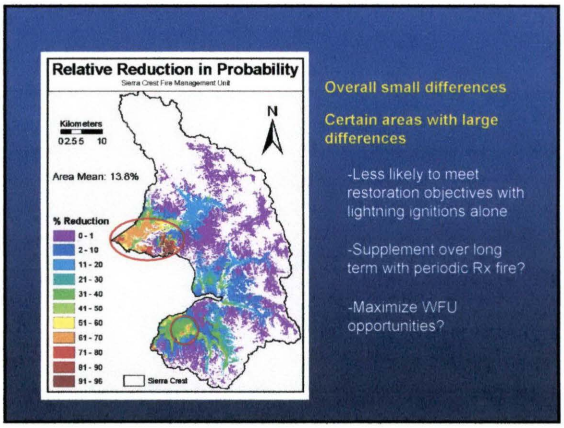
Probability of burning from FMU lightning ignitions only

Annual Probability of Burning
Kings & Kaweah Lightning Ignitions
Kilometers
0 2.5 5 10
N
Area Mean: 0.17
Probability
0.002
0.003 - 0.1
0.1 - 0.2
0.2 - 0.3
0.3 - 0.4
0.4 - 0.5
0.5 - 0.53
Sierra Crest
Annual Probability of Burning
Sierra Crest Lightning Ignitions
Kilometers
0 2.5 5 10
N
Area Mean: 0.12
Probability
0.002
0.003 - 0.1
0.1 - 0.2
0.2 - 0.3
0.3 - 0.4
0.4 - 0.5
0.5 - 0.53
Sierra Crest



Difference in Probability of Burning

Absolute Reduction in Probability
Sierra Crest Fire Management Unit
Kilometers
0 2.5 5 10
N
Area Mean: 0.04
Probability Reduction
0 - 0.01
0.01 - 0.1
0.1 - 0.2
0.2 - 0.3
0.3 - 0.34
Sierra Crest
Relative Reduction in Probability
Sierra Crest Fire Management Unit
Kilometers
0 2.5 5 10
N
Area Mean: 13.8%
% Reduction
0 - 1
2 - 10
11 - 20
21 - 30
31 - 40
41 - 50
51 - 60
61 - 70
71 - 80
81 - 90
91 - 96
Sierra Crest



Relative Reduction in Probability
Sierra Crest Fire Management Unit
Kilometers
0 2.5 5 10
N
Area Mean: 13.8%
% Reduction
0 - 1
2 - 10
11 - 20
21 - 30
31 - 40
41 - 50
51 - 60
61 - 70
71 - 80
81 - 90
91 - 96
Sierra Crest

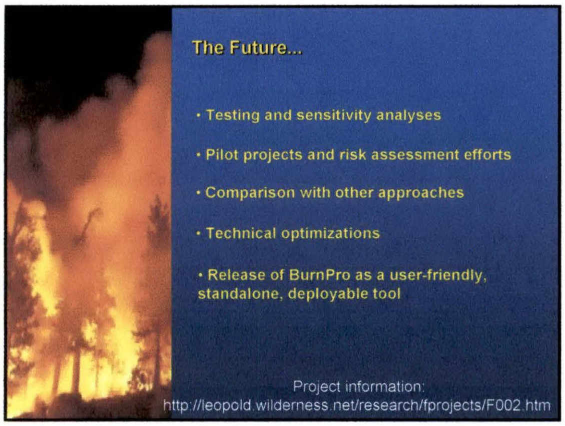
Overall small differences

Certain areas with large differences

-Less likely to meet restoration objectives with lightning ignitions alone

-Supplement over long term with periodic Rx fire?

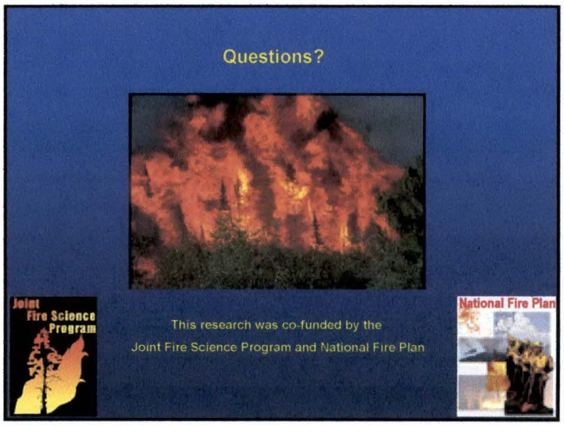
-Maximize WFU opportunities?



The Future...

- Testing and sensitivity analyses
- Pilot projects and risk assessment efforts
- Comparison with other approaches
- Technical optimizations
- Release of BurnPro as a user-friendly, standalone, deployable tool

Project information:
http://leopold.wilderness.net/research/fprojects/F002.htm



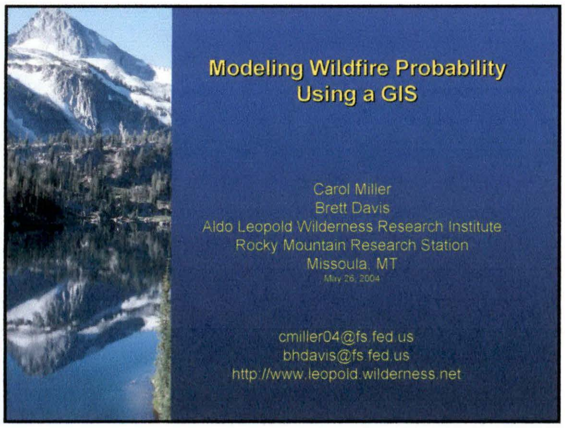
Questions?

This research was co-funded by the
Joint Fire Science Program and National Fire Plan

Joint Fire Science Program
National Fire Plan

American Society for Photogrammetry and Remote Sensing

Modeling wildfire probability using a GIS. Invited presentation at American Society for Photogrammetry and Remote Sensing Conference, Denver, CO, May 2004.



Modeling Wildfire Probability Using a GIS

Carol Miller
Brett Davis
Aldo Leopold Wilderness Research Institute
Rocky Mountain Research Station
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May 26, 2004

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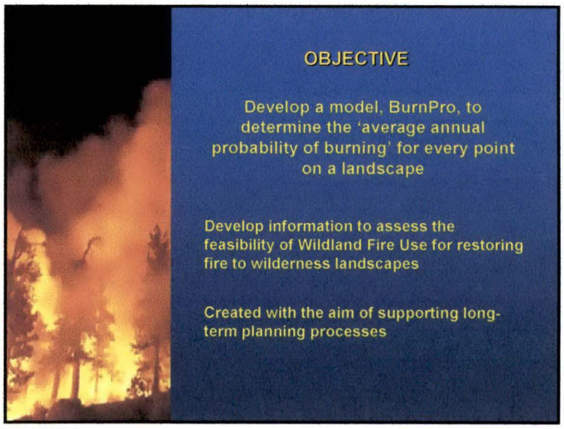
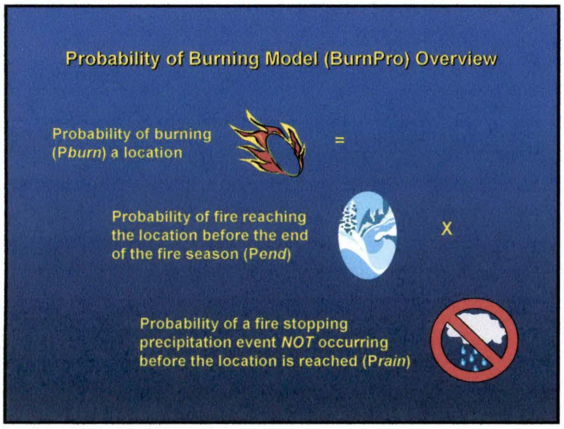


OBJECTIVE

Develop a model, BurnPro, to determine the 'average annual probability of burning' for every point on a landscape

Develop information to assess the feasibility of Wildland Fire Use for restoring fire to wilderness landscapes

Created with the aim of supporting long-term planning processes

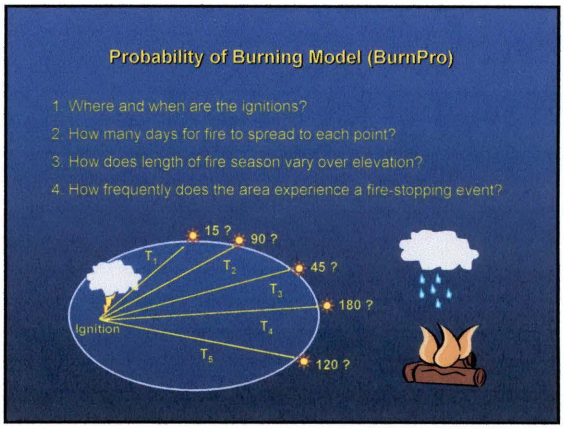


Probability of Burning Model (BurnPro) Overview

Probability of burning (*Pburn*) a location =

Probability of fire reaching the location before the end of the fire season (*Pend*) X

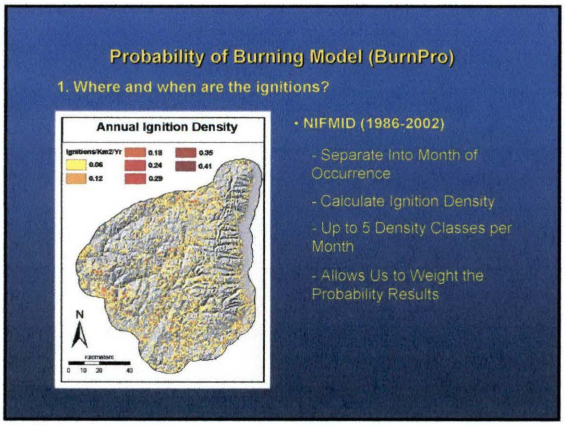
Probability of a fire stopping precipitation event *NOT* occurring before the location is reached (*Prain*)



Probability of Burning Model (BurnPro)

1. Where and when are the ignitions?
2. How many days for fire to spread to each point?
3. How does length of fire season vary over elevation?
4. How frequently does the area experience a fire-stopping event?

15 ?
90 ?
45 ?
180 ?
120 ?
T_1
T_2
T_3
T_4
T_5
Ignition

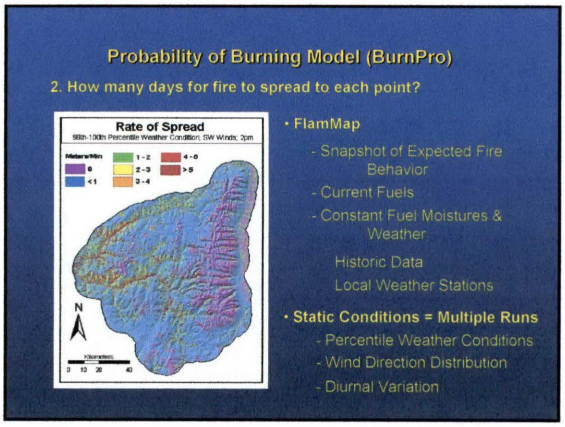


Probability of Burning Model (BurnPro)

1. Where and when are the ignitions?

Annual Ignition Density
Ignitions/Km2/Yr
0.06
0.12
0.18
0.24
0.29
0.35
0.41
N
Kilometers
0 10 20 40

- NIFMID (1986-2002)
  - Separate Into Month of Occurrence
  - Calculate Ignition Density
  - Up to 5 Density Classes per Month
  - Allows Us to Weight the Probability Results

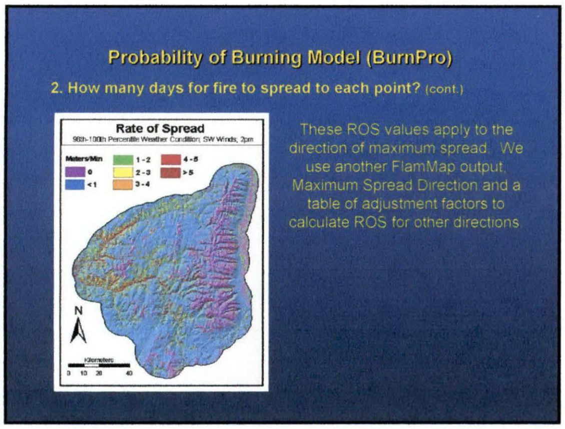


Probability of Burning Model (BurnPro)

2. How many days for fire to spread to each point?

Rate of Spread
98th-100th Percentile Weather Condition; SW Winds; 2pm
Meters/Min
0
<1
1 - 2
2 - 3
3 - 4
4 - 5
>5
N
Kilometers
0 10 20 40

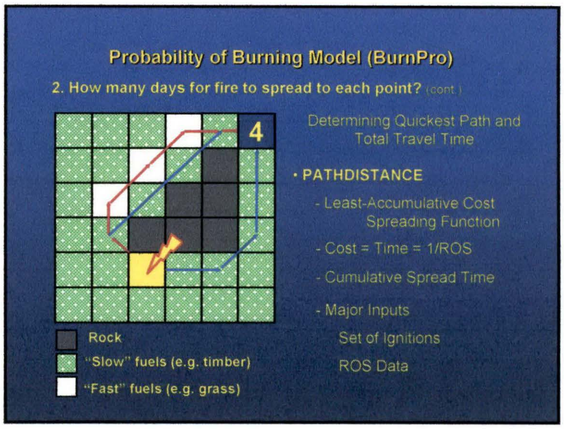
- FlamMap
  - Snapshot of Expected Fire Behavior
  - Current Fuels
  - Constant Fuel Moistures & Weather
    - Historic Data
    - Local Weather Stations
- Static Conditions = Multiple Runs
  - Percentile Weather Conditions
  - Wind Direction Distribution
  - Diurnal Variation



Probability of Burning Model (BurnPro)

2. How many days for fire to spread to each point? (cont.)

These ROS values apply to the direction of maximum spread. We use another FlamMap output, Maximum Spread Direction and a table of adjustment factors to calculate ROS for other directions.



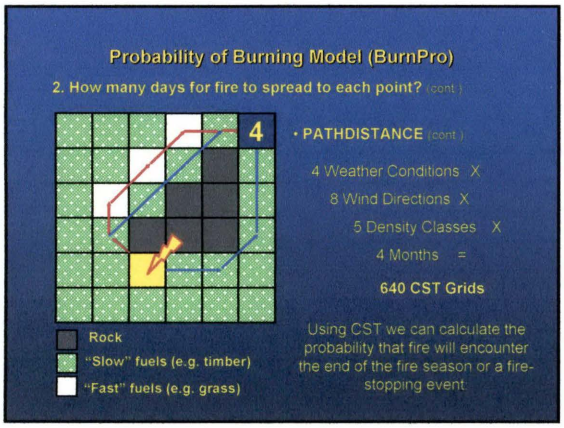
Probability of Burning Model (BurnPro)

2. How many days for fire to spread to each point? (cont.)

Determining Quickest Path and Total Travel Time

- **PATHDISTANCE**
  - Least-Accumulative Cost Spreading Function
  - Cost = Time = 1/ROS
  - Cumulative Spread Time
  - Major Inputs
    Set of Ignitions
    ROS Data

Rock
"Slow" fuels (e.g. timber)
"Fast" fuels (e.g. grass)



Probability of Burning Model (BurnPro)

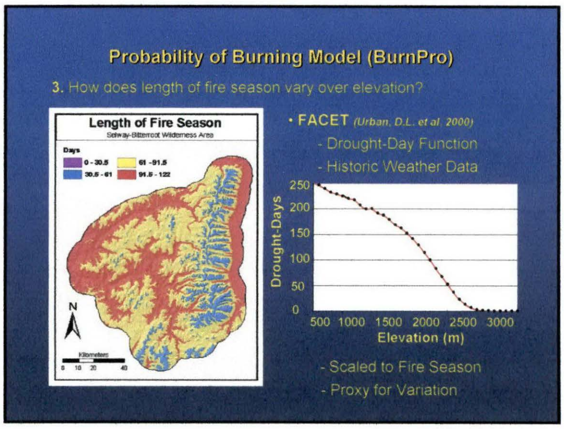
2. How many days for fire to spread to each point? (cont.)

- **PATHDISTANCE** (cont.)

4 Weather Conditions X
8 Wind Directions X
5 Density Classes X
4 Months =
640 CST Grids

Using CST we can calculate the probability that fire will encounter the end of the fire season or a fire-stopping event.

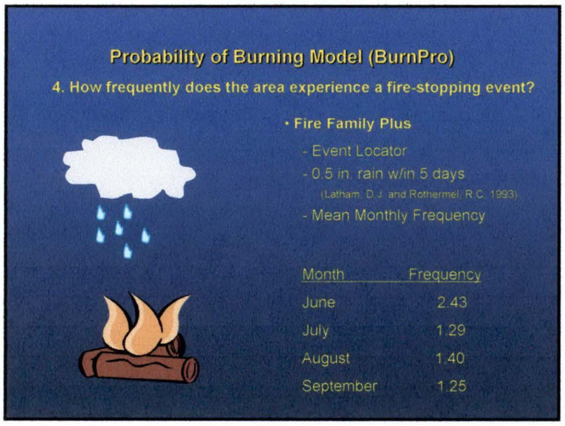
Rock
"Slow" fuels (e.g. timber)
"Fast" fuels (e.g. grass)



Probability of Burning Model (BurnPro)

3. How does length of fire season vary over elevation?

- **FACET** *(Urban, D.L. et al. 2000)*
  - Drought-Day Function
  - Historic Weather Data
  - Scaled to Fire Season
  - Proxy for Variation

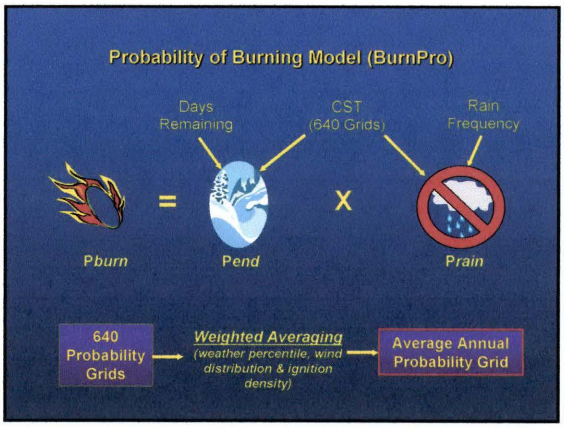


Probability of Burning Model (BurnPro)

4. How frequently does the area experience a fire-stopping event?

- **Fire Family Plus**
  - Event Locator
  - 0.5 in. rain w/in 5 days
    (Latham, D.J. and Rothermel, R.C. 1993)
  - Mean Monthly Frequency

Month	Frequency
June	2.43
July	1.29
August	1.40
September	1.25

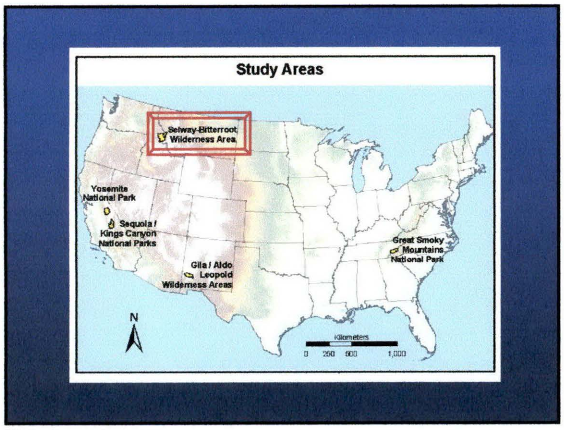


Probability of Burning Model (BurnPro)

Days Remaining
CST (640 Grids)
Rain Frequency

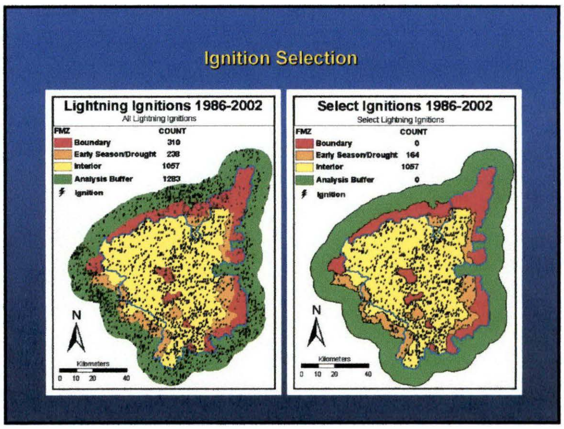
Pburn = **Pend** X **Prain**

640 Probability Grids → ***Weighted Averaging*** *(weather percentile, wind distribution & ignition density)* → **Average Annual Probability Grid**



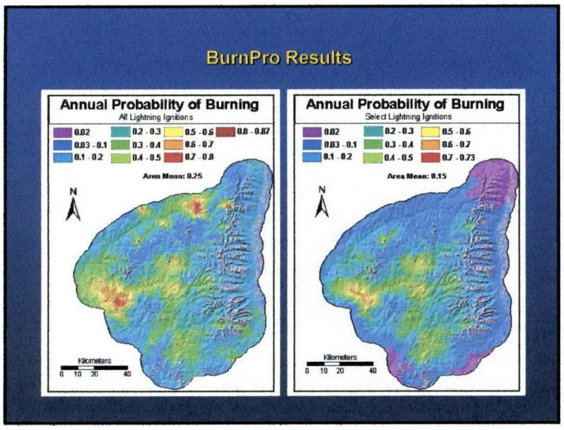
Study Areas

Selway-Bitterroot Wilderness Area
Yosemite National Park
Sequoia / Kings Canyon National Parks
Gila / Aldo Leopold Wilderness Areas
Great Smoky Mountains National Park
N
Kilometers
0 250 500 1,000



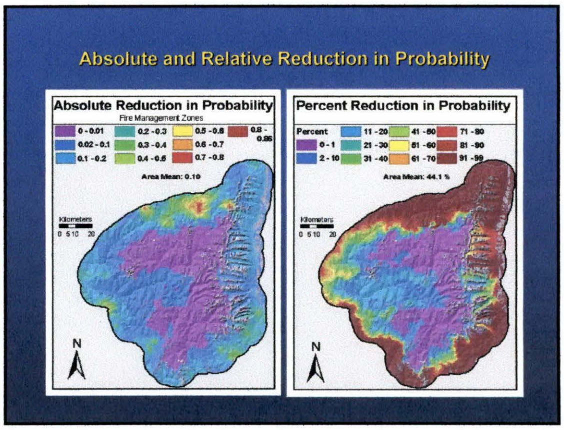
Ignition Selection

Lightning Ignitions 1986-2002
All Lightning Ignitions
FMZ COUNT
Boundary 310
Early Season/Drought 238
Interior 1057
Analysis Buffer 1283
Ignition
N
Kilometers
0 10 20 40
Select Ignitions 1986-2002
Select Lightning Ignitions
FMZ COUNT
Boundary 0
Early Season/Drought 164
Interior 1057
Analysis Buffer 0
Ignition
N
Kilometers
0 10 20 40



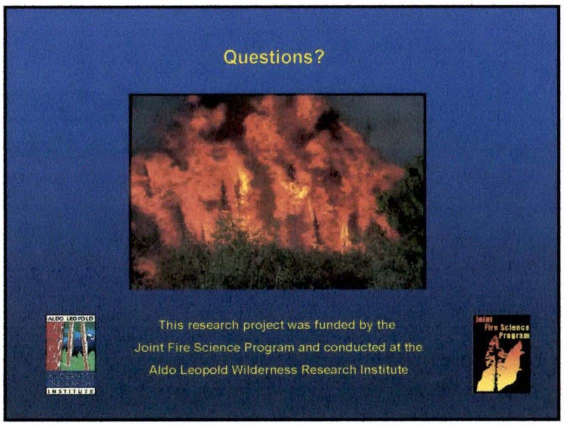
BurnPro Results

Annual Probability of Burning
All Lightning Ignitions
0.02
0.03 - 0.1
0.1 - 0.2
0.2 - 0.3
0.3 - 0.4
0.4 - 0.5
0.5 - 0.6
0.6 - 0.7
0.7 - 0.8
0.8 - 0.87
Area Mean: 0.25
N
Kilometers
0 10 20 40
Annual Probability of Burning
Select Lightning Ignitions
0.02
0.03 - 0.1
0.1 - 0.2
0.2 - 0.3
0.3 - 0.4
0.4 - 0.5
0.5 - 0.6
0.6 - 0.7
0.7 - 0.73
Area Mean: 0.15
N
Kilometers
0 10 20 40



Absolute and Relative Reduction in Probability

Absolute Reduction in Probability
Fire Management Zones
0 - 0.01
0.02 - 0.1
0.1 - 0.2
0.2 - 0.3
0.3 - 0.4
0.4 - 0.5
0.5 - 0.6
0.6 - 0.7
0.7 - 0.8
0.8 - 0.86
Area Mean: 0.10
Kilometers
0 5 10 20
N
Percent Reduction in Probability
Percent
0 - 1
2 - 10
11 - 20
21 - 30
31 - 40
41 - 50
51 - 60
61 - 70
71 - 80
81 - 90
91 - 99
Area Mean: 44.1 %
Kilometers
0 5 10 20
N



Questions?

This research project was funded by the Joint Fire Science Program and conducted at the Aldo Leopold Wilderness Research Institute

Technical Fire Management

Lecture notes and slide presentation from Technical Fire Management, Bothell, WA, October 2004.

INSTRUCTOR: Carol Miller

LESSON: Prediction of burn probabilities

COURSE: TFM-19 Module VI (October 13, 2004)

OBJECTIVES:

Upon the successful completion of this unit, the student will:

- Understand data requirements and general procedures for estimating probability of burning using the model BurnPro.
- Appreciate the underlying assumptions in the BurnPro approach so that model results are responsibly and credibly interpreted.
- Be familiar with one example that links existing data and modeling tools to estimate and spatially map the probability of burning.
- Be inspired to apply existing tools in new ways to answer management questions of his/her own.

NARRATIVE:

I. Introduction

A. Lesson objectives.

B. Lesson organization.

C. Probability of burning and BurnPro

1. Purpose and need:
    - Knowing where fire is most likely to burn within a landscape: Are some areas more or less prone to being burned than others? Such information is needed to assess risk, prioritize fuel treatments and do prevention planning.
    - Planning for wildland fire use (WFU) also requires an understanding of where the most frequent opportunities for WFU are within a landscape. This information is needed for developing fire management plans (FMP) and for go/no-go decision support.
    - Anticipating the consequences of implementing a particular FMP: Does the FMP affect how often we can expect fire to burn? This information can provide a reality check on our expectations.
2. Contrast with ignition probability and RERAP probabilities:

- Probability of burning is different from probability of ignition. Many assessments have derived and used probability of ignition, whereby #ignitions per unit area is computed for a particular time period. Probability of ignition is very useful for examining risk at a coarse scale, but not very useful at finer scales of the project level.
- Probability of burning depends on the number of ignitions in a particular area, but also on fire spread in a *spatial context*. Methods demonstrated in this lesson are intended to help with planning at the mid scale and/or project level.
- Probability of burning is also different from probabilities generated in RERAP. RERAP is a nonspatial analysis tool analysis for a single fire incident (FRAMES 2003). Probability of burning, as discussed in this lesson, represents the cumulative probability of many events, averaged over many years. The intended planning horizon (several years to decades) is different from RERAP's single incident timeframe.

3. What BurnPro does:
   - Considers ignitions, rate of fire spread, time available for fire spread, and topography, all in a *spatial context*. It integrates the timing and location of ignitions, rate of spread of fire (as it is affected by fuels, topography and weather), length of fire season as it varies over elevation, and frequency of fire-stopping events (i.e., rain) during the fire season.
   - Provides an estimate of annual probability of burning using data from many years and multiple events that would occur under a range of weather conditions.
   - Estimates annual probability of burning value for every cell on raster landscape
   - Generates *continuous* values (not categorical).
   - Supports long-term planning processes such as fire management planning. It is not suitable for most incident management applications, but can be useful for the type of pre-planning that supports a go/no-go decision.
   - Computes the probability of burning a location as the product of the probability that fire reaches the location before the end of the fire season (P*End*) and the probability that fire will reach the location before a fire-stopping event (P*NoRain*).
   - Although BurnPro generates numerical values representing probability, these should be interpreted only as *relative* values.

II. The BurnPro approach

A. Written in ArcGIS AML (Arc Macro Language). Runs in ArcGIS version 7.2 or higher.

B. Several data layers (GIS) are needed for input:

1. Monthly ignition point coverages. Data available from http://famweb.nwcg.gov/weatherfirecd

2. Rate-of-spread (m/min) and direction-of-maximum-spread grids for selected percentile weather conditions. Percentile weather conditions are determined using Spread Component Index generated from FireFamily+. Rate-of-spread and direction-of-maximum-spread grids are generated from FlamMap .

3. Elevation (m) grid, e.g., from a digital elevation model (DEM).

4. Average length-of-fire-season (days) grid. This might be derived from Daymet variables like growing-degree-days (http://daymet.org), from drought-days computed by FACET (Urban et al. 2000), or by using expert judgment about how fire season varies across the landscape.

5. Cell size has implications for processing time, which depends also on the number of ignitions, the number of ignition density grids, and computer capability. We have found that a cell size of 90m is usually feasible. For example, a run at 90m resolution for Yosemite National Park with all lightning ignitions 3.5 to 4 hours to run on a computer with a 1.67 GHz Pentium 4 and 1Gb RAM.

C. Other data required:

1. Historical weather from local weather station(s): daily observations throughout the fire season of temperature, relative humidity, precipitation, wind speed, wind direction. Recommend ~20 years or more of data.

2. Frequency of fire-stopping precipitation events, by month. The average monthly frequency of fire-stopping events can be computed using FireFamily+. These events might be defined as a certain amount of rain within a given time period (e.g., 0.5 inches of rain within a 5-day period).

3. Frequency distribution of wind directions. Daily observations of wind directions can be analyzed using a simple spreadsheet program like Excel to determine the relative proportion of observations falling into 8 compass directions.

D. Status of BurnPro – still under development

1. This version of BurnPro has yet to be peer-reviewed. Although an early prototype was peer-reviewed and published (Miller 2003), the current version is substantially different. Manuscript is currently in preparation.

2. Model is still undergoing testing and verification.

3. Results should be viewed with some skepticism and applied with caution.

E. Outline of approach, to compute P*End* and P*NoRain*.

1. Length of fire season
    - Longer periods of time available for fire to spread should lead to higher probability of burning.
    - This length of time—the length of fire season—varies across a landscape according to elevation, aspect, topographic position, etc.
    - In examples shown in this lesson, only variations with elevation have been accounted for. A fairly complicated soil-water-balance model (Urban et al. 2000) and its estimates of "drought-days" for different elevations were used to approximate how length of fire season varies with elevation.
    - There are many other possible ways to map fire season across the landscape. For example, estimates of growing-degree-days from Daymet (http://daymet.org) could be used as a proxy for length of fire season, or expert knowledge/opinion of the area could be used.

2. Rain
    - Less frequent heavy rain events should lead to higher probability of burning. How frequently does the area experience these fire-stopping events?
    - Use FireFamily+'s event locator and historic weather data to determine number of times the area experiences a fire-stopping rain event. In this case, the number of times more than 0.5 inches of rain occurred within a 5-day period was counted. These counts were used to determine the average frequency of occurrence. For example, analysis of weather data for the Selway-Bitterroot Wilderness indicates that June typically sees an average of 2.43 fire-stopping events, July 1.29, August 1.40 and September 1.25.

3. Ignitions
    - Higher density of ignitions should lead to higher probability of burning. Ignitions that occur early in the season have a longer opportunity to burn. Therefore, all things being equal, the more ignitions occurring early in the season should lead to a higher probability of burning. Where (density) and when (which month) are ignitions?
    - Historic ignition data are available from http://famweb.nwcg.gov/weatherfirecd. These data contain geographic location (latitude/longitude), date, and cause (e.g., lightning or human-caused).
    - These point data are separated into point coverages by month of occurrence. From these point coverages, ignition densities are calculated using the POINTSTATS function in Arc. From these values, up to 5 density grids are created, representing low to high density classes for each month of occurrence.
    - For example, if there are 4 months in the fire season (e.g., June-September) and 5 density classes, the result will be 20 ignition grids. These separate month and density classes will allow the weighting of probability results when the average annual probability of burning is calculated (the last step in the BurnPro approach). Weights are assigned according to frequency of occurrence. For example, probabilities generated using density class 5 will be weighted 5 times more heavily than those generated using density class 1.

- Recommend using ~15 years or more of ignition data. Note that location accuracy before 1986 is generally poor.

4. Rate of spread (ROS)

   - Rapid fire spread should lead to higher probability of burning. How quickly does fire spread across the landscape?
   - Use FlamMap to calculate ROS. FlamMap provides a snapshot of expected fire behavior for every pixel on a raster landscape based on current fuels, slope, aspect, fuel moistures conditioned under specified weather conditions, and constant wind.
   - Because FlamMap calculates ROS for static conditions, multiple runs are necessary to account for variation in weather conditions and wind direction.
   - Multiple FlamMap runs represent ROS under 8 different wind directions and 4 different percentile weather conditions. Percentile weather conditions are defined using FireFamily+ and historic weather data from local weather stations. For example, if there are 8 wind directions (N, NE, E, SE, S, SW, W, NW) and 4 weather classes (low: 0-79%, moderate: 80-89%, high: 90-97%, extreme: 98-100%), 32 ROS grids will be created.
   - Frequency distribution of wind directions and percentiles for the weather classes will be used to weight the probability results when the average annual probability of burning is calculated (the last step in the BurnPro approach). Probabilities calculated for these conditions will be weighted accordingly when the annual average is computed. Note that the 99th percentile weather condition only occurs 1% of the time.

5. Cumulative spread time (CST)

   - The longer it takes fire to reach a location, the lower the probability of burning should be. Both P*End* and P*NoRain* depend on knowing how long it would fire to spread to a location. This length of time is compared to the length of fire season in P*End*. In P*NoRain*, it is compared essentially to the length of time between rain events.
   - To compute the number of days for fire to spread from ignition locations to all other points on the landscape, BurnPro uses the ArcInfo function Pathdistance.
   - Pathdistance is a least-accumulative cost spreading function. It computes the cheapest path and total cost of traveling to each cell in a grid. Instead of cost, we are interested in time. Basically, Pathdistance figures out where the path of least resistance is on the landscape and computes the total cost, or time, it takes to travel that path. Pathdistance also accounts for the influence of a directional force such as wind.
   - Pathdistance requires a Source grid and a Cost grid. In BurnPro, the Source grid is one of the ignition density grids. The Cost grid is Time, derived from any one of the ROS grids with simple arithmetic (dividing the dimension of a grid cell, e.g., 90m, by the ROS yields the time it would take for fire to traverse that cell).
   - For any location, there are almost an infinite number of paths that fire could take to get there. There is only one quickest path, and that is the path that would

result in the lowest cumulative spread time (CST). In the example, the quickest path is through the "fast" fuels, shown in white, even though it is actually a longer path in terms of pure distance.

- BurnPro uses Pathdistance to generate CST grids for each unique combination of ignition (source) grid x Time (cost) grid. If there are 20 ignition grids (4 months x 5 density classes) and 32 Time grids (derived from 32 ROS grids: 4 weather classes x 8 wind directions), 640 CST grids will be generated (20 ignition grids x 32 Time grids.

6. Probabilities P*End* and P*NoRain*
   - P*End* is the probability that fires can reach a location before the end of the fire season. It is calculated from the length of fire season and CST. Currently, the Weibull function is used: P*End* = $\exp[-(\text{CST/season length})^{\eta}]$. η is a parameter derived from the distribution of season lengths and it reflects the interannual variation in season length.
   - P*NoRain* is the probability that fires can reach a location before a fire-stopping event occurs. It is calculated using CST and the monthly frequency of fire-stopping rain events. The probability that a significant rain event occurs within the time span of the CST is P*Rain*. The probability that such a rain event does not occur is P*NoRain* = 1 - P*Rain*.
   - P*Burn* is the product of P*End* and P*NoRain*.
   - Multiple P*Burn* grids are generated as a result of these calculations using the multiple CST grids. If there are 640 CST grids, there will be 640 P*Burn* grids.
7. Weighted average
   - The multiple P*Burn* grids are combined through a weighted averaging approach to generate a single map of annual probability of burning.
   - Relative weights are assigned to individual P*Burn* grids according to the frequency of the various weather conditions, wind direction distributions and ignition densities.
8. Average annual probability of burning
   - Resulting map of probability of burning can be viewed in terms of risk. Areas of high probability of burning can be overlaid with socio-economic or ecological values to identify where risks from fire are high. These might be priorities for fuel treatments or prevention planning.
   - The resulting map of probability of burning can also be viewed in terms of opportunities for WFU. WFU opportunities may be fairly common or frequent in areas with high probability of burning. If a suppression decision has to be made in these areas due to external factors, another opportunity for WFU may occur relatively soon. On the other hand, WFU opportunities are rare in areas with low probability of burning.

III. Key assumptions and uncertainties

A. Although BurnPro generates numerical values representing probability, these should be interpreted only as relative values. They do not represent absolute probabilities. In other words, it is appropriate to interpret a value of 0.50 as being 5 times greater than a value of 0.10. But a value of 0.50 should not be interpreted as meaning that there is a 50 percent chance of burning.

B. The ROS spread grids that BurnPro uses are generated using maps of current fuels. Therefore, the output from BurnPro does not take into account changes in fuels over time due to succession or fires.

C. Calculations by Pathdistance are very dependent on how many ignition sources there are in the Source grid, and on how these are distributed in space. Therefore, the length of the record used for historical ignitions will likely have an influence on BurnPro output. Running BurnPro with randomly located ignitions versus historical locations is useful.

D. The equation used for P*End* may not be the best equation to use. We are looking into alternative ways to calculate probabilities.

E. Drought-days from FACET or growing-degree-days from Daymet may not be the best proxy for length of fire season as it varies across the landscape. Furthermore, the length of fire season used represents an average year. In extreme years, ignitions occur in areas that wouldn't be "in-season" in a normal year. BurnPro eliminates these ignitions that fall outside the season.

F. Historic weather data from only one or a few weather stations are extrapolated to a large area.

G. Ignitions are handled on a monthly basis and calculations of probability are based on the assumption that ignitions occur mid-month.

H. Definition of fire-stopping events as 0.5 inch in 5-day period was developed for the northern Rockies. Different definitions will impact results.

IV. Results, analyses and sensitivities

A. Fire Management Plan analysis

1. Three national parks and two FS wilderness areas are serving as study areas for pilot application of BurnPro. BurnPro is being used to help evaluate FMP objectives.

2. Sequoia-Kings Canyon National Park has been involved with interagency fire planning in the southern Sierra. We extended our analysis beyond Park boundaries and used the watershed boundaries that this planning effort has adopted.

3. The Sierra Crest Fire Management Unit (FMU) is the focus of our analysis. The current FMP indicates that the Sierra Crest FMU is to be managed for natural processes applying WFU as the primary tool. We used BurnPro to evaluate how suppression outside the FMU affects the rate of burning within the FMU. In other words, by how much is the probability of burning reduced when we eliminate the importation of fire from outside the Sierra Crest FMU?

4. Two ignition scenarios for BurnPro:
    - All lightning ignitions for the entire study area

- Only lightning ignitions occurring within the Sierra Crest FMU

5. Results:
    - When ignitions outside the FMU are eliminated, the probability of burning is reduced from an average of 0.17 to 0.13.
    - Looking at the difference between the two scenarios makes a direct point-to-point comparison. For most of the FMU, the relative difference is low, indicating that the effect of eliminating ignitions outside the FMU is small. There are, however, a few areas showing a dramatic difference in probability.
    - Areas with dramatic differences between the two scenarios are areas where it could be especially difficult to restore fire to a natural frequency due to management objectives of adjacent lands. These are areas where opportunities for WFU should be maximized and where periodic prescribed burning over the long term could be warranted.

B. Sensitivity analysis: frequency of fire-stopping events

1. Increasing the frequency of fire-stopping events should decrease the probability of burning.
2. For the Gila Wilderness these events are defined as 0.5 inches of rain occurring in 5 days. We increased monthly frequency of fire-stopping events by 50% and compared the resulting probability of burning with the "normal" case.
3. Results:
    - Increasing the frequency of fire-stopping events does decrease the probability of burning and the difference is noticeable.
    - The degree of difference varies spatially. Some places on the landscape are apparently more sensitive to changes in frequency of heavy rains.

C. Sensitivity analysis: length of fire season

1. Increasing the length of the fire season should increase the probability of burning.
2. For Yosemite National Park, we increased the length of the fire season by shifting the season uphill by 500m. This approximately doubles the amount of area that has a 4-month or longer fire season.
3. Results:
    - Effect on annual probability of burning isn't very dramatic at a landscape scale. This suggests that, generally speaking, BurnPro isn't very sensitive to length of fire season. This variable has a fairly high degree of uncertainty, but it may not be very important to get it right.
    - Direct point-to-point comparison reveals that there are places on the landscape that are highly sensitive to this variable.
    - Spatial context and configuration matter.

V. Prospectus

A. Resolve outstanding issues. During the development of this version of BurnPro, we have identified several issues that need to be resolved in the next version.

B. Continued testing and sensitivity analyses. The model will have a degree of sensitivity to each of the variables within it. It is important to understand the model's sensitivity, particularly to those variables we are most uncertain about or for which we lack good data.

C. Continued involvement with pilot study areas, incorporating feedback from staff. In addition to Selway-Bitterroot Wilderness, Gila Wilderness, Sequoia-Kings Canyon, Yosemite, and Great Smoky Mountains National Parks, BurnPro has been applied by TFM student Kevin Hillard on the Cloud Peak Wilderness in Wyoming, and is being evaluated for use in the Front Range Fuel Treatment Project in Harris Park, CO.

D. Test BurnPro's functions and compare its behavior with other approaches, including a model developed by the Canadian Forest Service.

E. Various technical optimizations to increase efficiency and reduce run-time.

F. Ultimately, work towards development of a user-friendly, stand-alone, deployable tool for use by fire management staff.

VI. References:

Davis, B. and Miller, C. 2004. Modeling Wildfire Probability Using a GIS. In: Proceedings of the ASPRS 2004 Annual Conference, Denver, USA. May 23-28. American Society for Photogrammetry and Remote Sensing, 2004. Available on CD.

FRAMES 2003. Fire Research and Management Exchange System, Fire Management Tools Online. [Online]. Available: http://www.frames.gov/tools/#RERAP [September 20, 2004]

Miller, C. 2003. The spatial context of fire: a new approach for predicting fire occurrence. Pages 27-34 in L.A. Brennan, et al. (eds.). National Congress on Fire Ecology, Prevention, and Management Proceedings, No. 1. Tall Timbers Research Station, Tallahassee, FL.

Urban, D.L. et al. 2000. Forest gradient response in Sierran landscapes: the physical template. *Landscape Ecology* 15: 603-620.

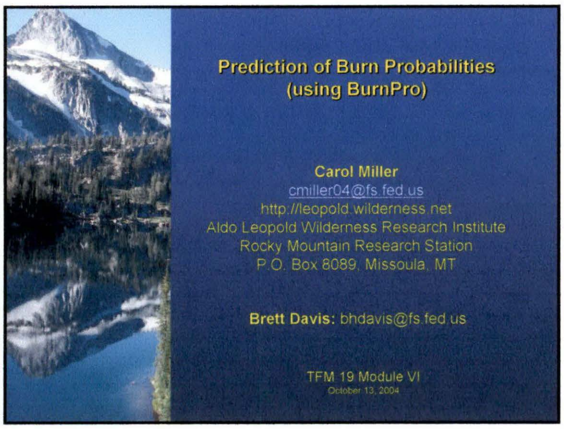
Links:

Daymet data and information: http://Daymet.org

Fire occurrence data: http://famweb.nwcg.gov/weatherfirecd

FlamMap files and information: http://fire.org/nav.mas?pages=flammap&mode=1

Project information on BurnPro: http://leopold.wilderness.net/research/fprojects/F002.htm



Prediction of Burn Probabilities (using BurnPro)

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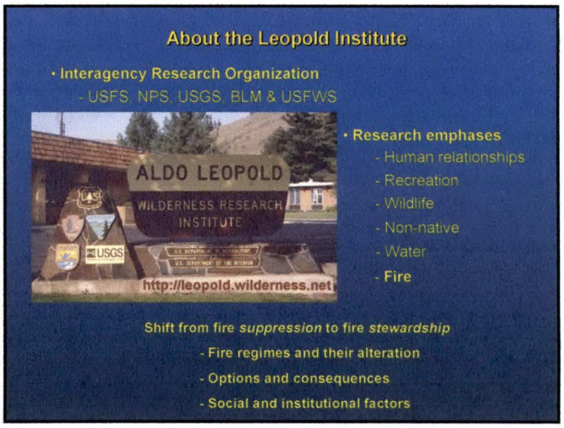
TFM 19 Module VI
October 13, 2004



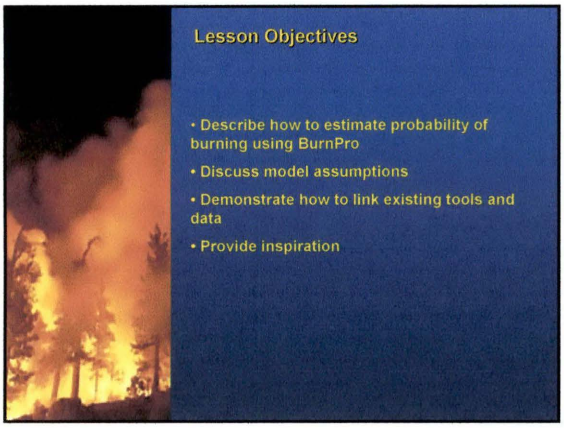
About the Leopold Institute

- Interagency Research Organization
  - USFS, NPS, USGS, BLM & USFWS

ALDO LEOPOLD
WILDERNESS RESEARCH INSTITUTE
USGS
http://leopold.wilderness.net

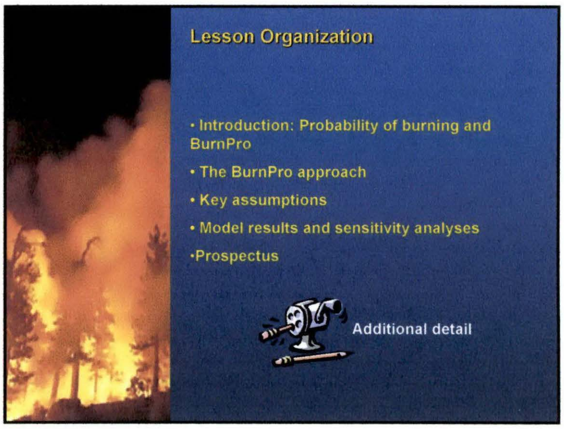
- Research emphases
  - Human relationships
  - Recreation
  - Wildlife
  - Non-native
  - Water
  - Fire

Shift from fire *suppression* to fire *stewardship*
- Fire regimes and their alteration
- Options and consequences
- Social and institutional factors



Lesson Objectives

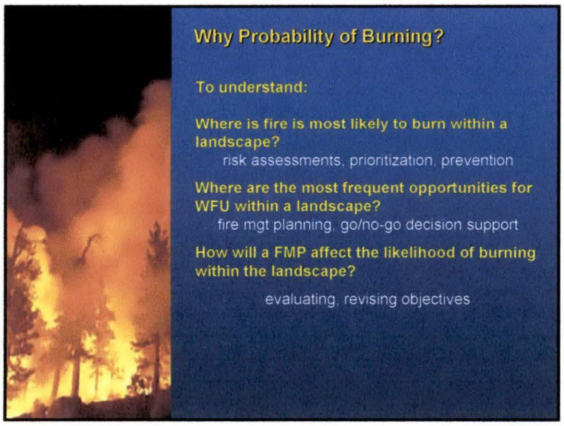
- Describe how to estimate probability of burning using BurnPro
- Discuss model assumptions
- Demonstrate how to link existing tools and data
- Provide inspiration



Lesson Organization

- Introduction: Probability of burning and BurnPro
- The BurnPro approach
- Key assumptions
- Model results and sensitivity analyses
- Prospectus

Additional detail



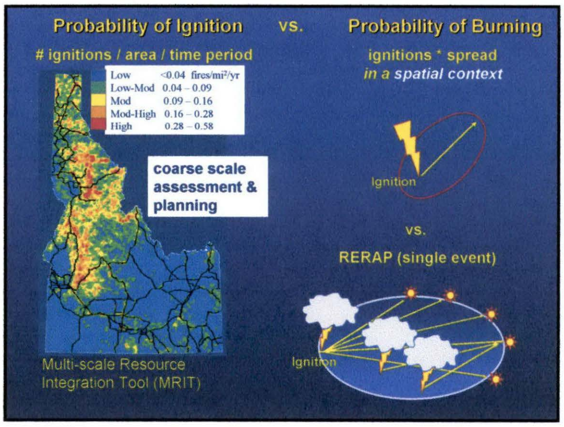
Why Probability of Burning?

To understand:

Where is fire is most likely to burn within a landscape?
risk assessments, prioritization, prevention

Where are the most frequent opportunities for WFU within a landscape?
fire mgt planning, go/no-go decision support

How will a FMP affect the likelihood of burning within the landscape?
evaluating, revising objectives



Probability of Ignition vs. Probability of Burning

ignitions / area / time period

Low <0.04 fires/mi²/yr
Low-Mod 0.04 – 0.09
Mod 0.09 – 0.16
Mod-High 0.16 – 0.28
High 0.28 – 0.58

coarse scale assessment & planning

Multi-scale Resource Integration Tool (MRIT)

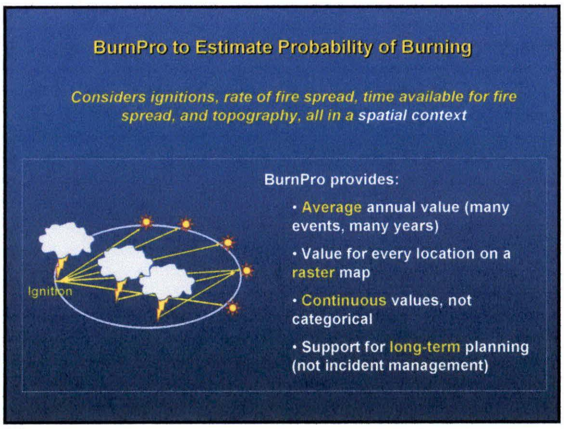
ignitions * spread
in a spatial context

Ignition

vs.

RERAP (single event)

Ignition

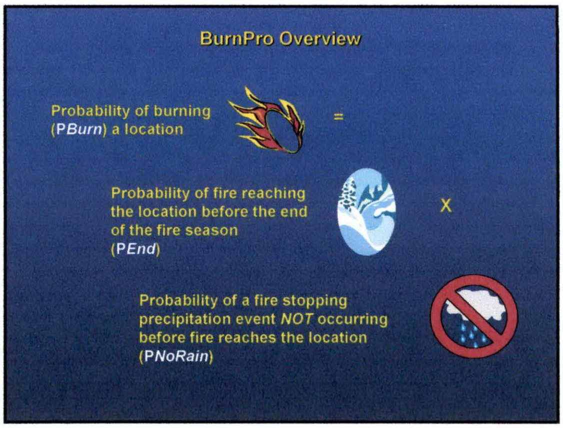


BurnPro to Estimate Probability of Burning

Considers ignitions, rate of fire spread, time available for fire spread, and topography, all in a spatial context

BurnPro provides:

- Average annual value (many events, many years)
- Value for every location on a raster map
- Continuous values, not categorical
- Support for long-term planning (not incident management)



BurnPro Overview

Probability of burning (P*Burn*) a location =

Probability of fire reaching the location before the end of the fire season (P*End*) X

Probability of a fire stopping precipitation event *NOT* occurring before fire reaches the location (P*NoRain*)

Data and Tools Required

Currently written as ArcGIS AML

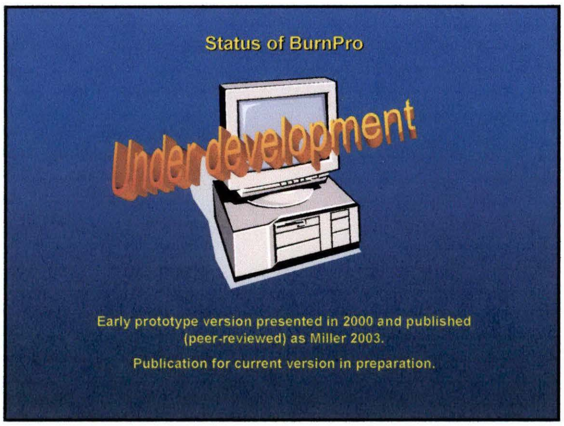
Input data layers required:

- Monthly ignition point coverages
  - from NIFMID or SACS
- ROS grids and Direction-of-Maximum-ROS grids by percentile weather condition and wind direction
  - percentile weather conditions from FireFamily+
  - ROS and DoMR from FLAMMAP
- Elevation (e.g., DEM)
- Average length of fire season in days (grid)
  - from FACET, Daymet, or other

Data and Tools Required (cont'd)

Other data needs:

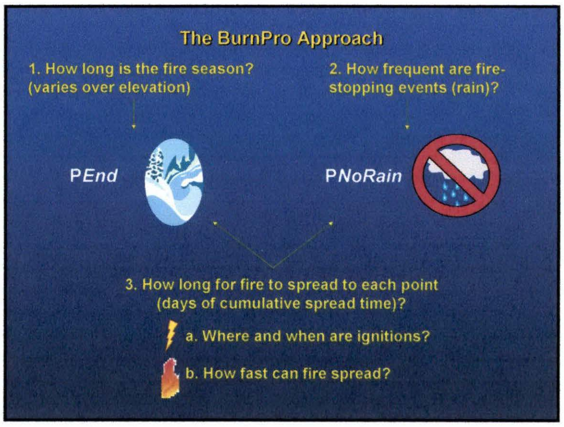
- Average frequency of fire stopping events by month
  - from FireFamily+
- Frequency distribution of wind directions


Under development

Status of BurnPro

Early prototype version presented in 2000 and published (peer-reviewed) as Miller 2003.

Publication for current version in preparation.



The BurnPro Approach

1. How long is the fire season? (varies over elevation)

2. How frequent are fire-stopping events (rain)?

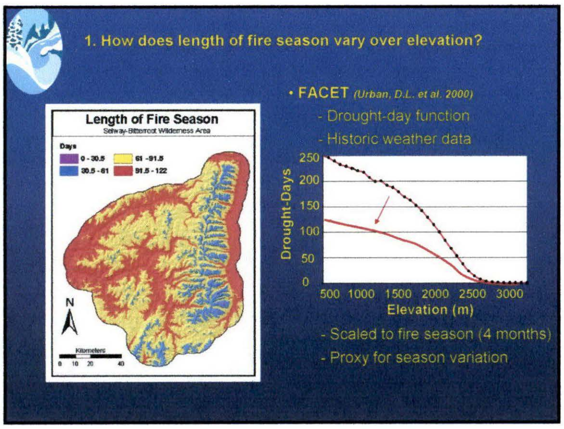
P*End*

P*NoRain*

3. How long for fire to spread to each point (days of cumulative spread time)?

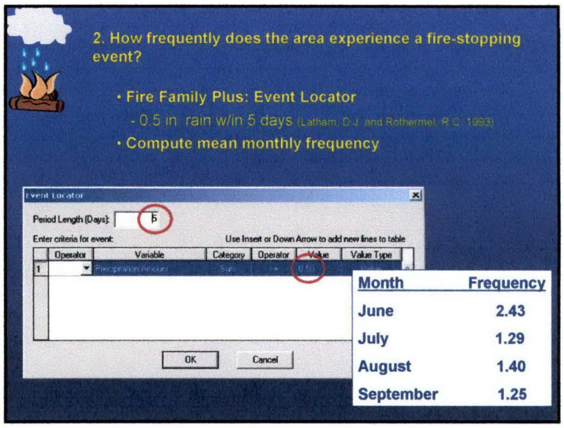
a. Where and when are ignitions?

b. How fast can fire spread?



1. How does length of fire season vary over elevation?

- FACET *(Urban, D.L. et al. 2000)*
  - Drought-day function
  - Historic weather data
  - Scaled to fire season (4 months)
  - Proxy for season variation



2. How frequently does the area experience a fire-stopping event?

- Fire Family Plus: Event Locator
  - 0.5 in. rain w/in 5 days (Latham, D.J. and Rothermel, R.C. 1993)
- Compute mean monthly frequency

Event Locator

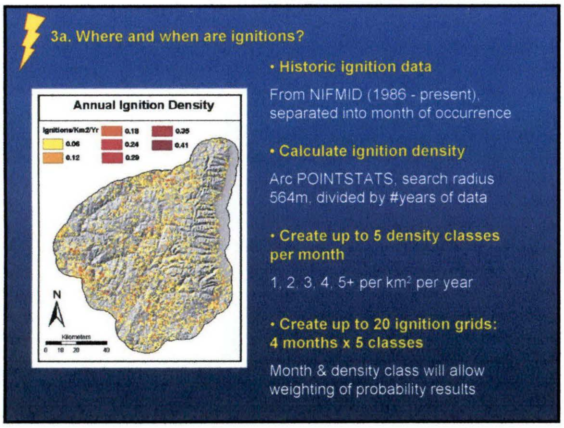
Period Length (Days): 5

Enter criteria for event:

Use Insert or Down Arrow to add new lines to table

	Operator	Variable	Category	Operator	Value	Value Type
1		Precipitation Amount	Sum	>=	0.50	[illegible]

Month	Frequency
June	2.43
July	1.29
August	1.40
September	1.25



3a. Where and when are ignitions?

- Historic ignition data

From NIFMID (1986 - present), separated into month of occurrence

- Calculate ignition density

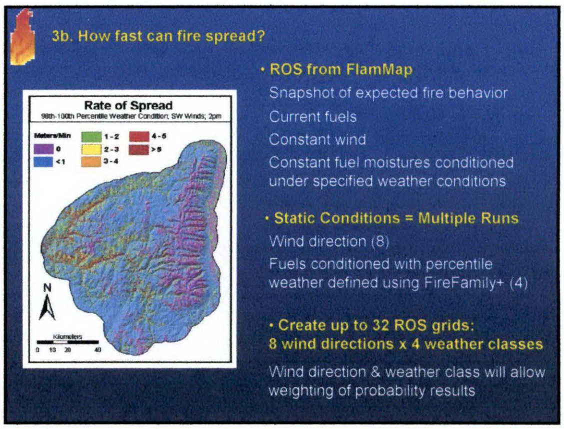
Arc POINTSTATS, search radius 564m, divided by #years of data

- Create up to 5 density classes per month

1, 2, 3, 4, 5+ per km^2 per year

- Create up to 20 ignition grids: 4 months x 5 classes

Month & density class will allow weighting of probability results



3b. How fast can fire spread?

- ROS from FlamMap

Snapshot of expected fire behavior

Current fuels

Constant wind

Constant fuel moistures conditioned under specified weather conditions

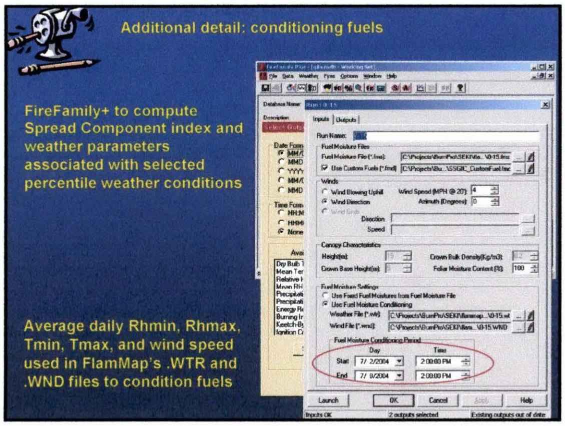
- Static Conditions = Multiple Runs

Wind direction (8)

Fuels conditioned with percentile weather defined using FireFamily+ (4)

- Create up to 32 ROS grids: 8 wind directions x 4 weather classes

Wind direction & weather class will allow weighting of probability results



Additional detail: conditioning fuels

FireFamily+ to compute Spread Component index and weather parameters associated with selected percentile weather conditions

Average daily Rhmin, Rhmax, Tmin, Tmax, and wind speed used in FlamMap's .WTR and .WND files to condition fuels

Run : 0-15

Fuel Moisture File (*.fms): C:\Projects\BurnPro\SEKI\fla...\0-15.fms

☑ Use Custom Fuels (*.fmd): C:\Projects\Bu...\SSGIC_CustomFuel.fmd

○ Wind Blowing Uphill

● Wind Direction

Wind Speed (MPH @ 20'): 4

Azimuth (Degrees): 0

Foliar Moisture Content (%): 100

○ Use Fixed Fuel Moistures from Fuel Moisture File

● Use Fuel Moisture Conditioning

Weather File (*.wtr): C:\Projects\BurnPro\SEKI\flammap...\0-15.wtr

Wind File (*.wnd): C:\Projects\BurnPro\SEKI\flam...\0-15.WND

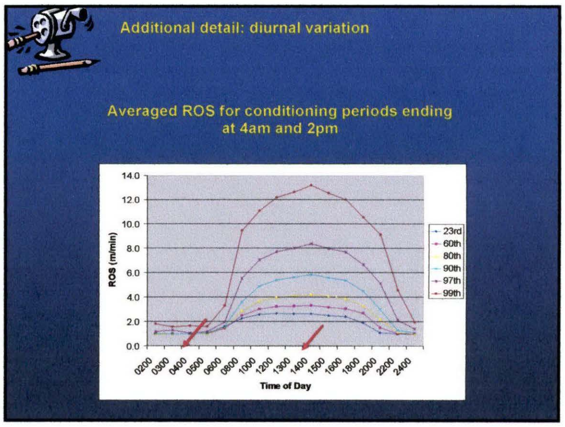
Fuel Moisture Conditioning Period

	Day	Time
Start	7/ 2/2004	2:00:00 PM
End	7/ 9/2004	2:00:00 PM

Inputs OK

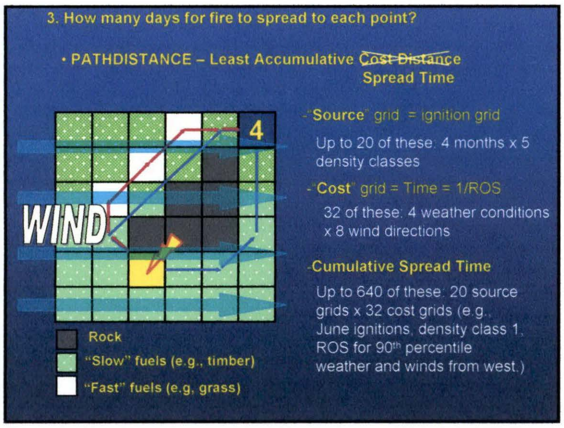
2 outputs selected

Existing outputs out of date



Additional detail: diurnal variation

Averaged ROS for conditioning periods ending at 4am and 2pm



3. How many days for fire to spread to each point?

- PATHDISTANCE – Least Accumulative ~~Cost Distance~~ Spread Time

-"**Source**" grid = ignition grid

Up to 20 of these: 4 months x 5 density classes

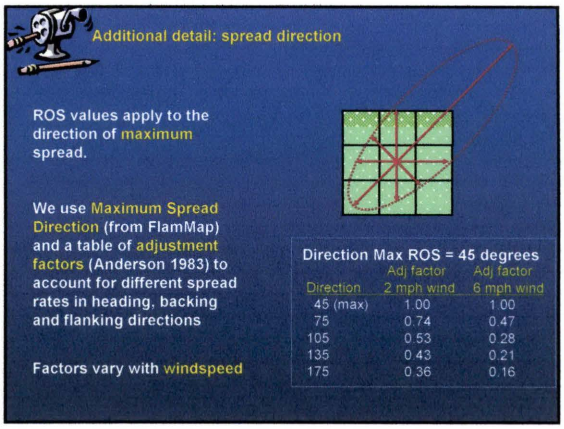
-"**Cost**" grid = Time = 1/ROS

32 of these: 4 weather conditions x 8 wind directions

-**Cumulative Spread Time**

Up to 640 of these: 20 source grids x 32 cost grids (e.g., June ignitions, density class 1, ROS for 90th percentile weather and winds from west.)

■ Rock
🟩 "Slow" fuels (e.g., timber)
☐ "Fast" fuels (e.g, grass)



Additional detail: spread direction

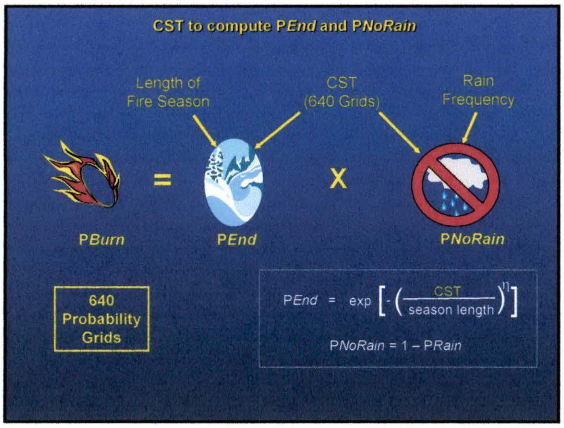
ROS values apply to the direction of maximum spread.

We use Maximum Spread Direction (from FlamMap) and a table of adjustment factors (Anderson 1983) to account for different spread rates in heading, backing and flanking directions

Factors vary with windspeed

Direction Max ROS = 45 degrees

Direction	Adj factor 2 mph wind	Adj factor 6 mph wind
45 (max)	1.00	1.00
75	0.74	0.47
105	0.53	0.28
135	0.43	0.21
175	0.36	0.16



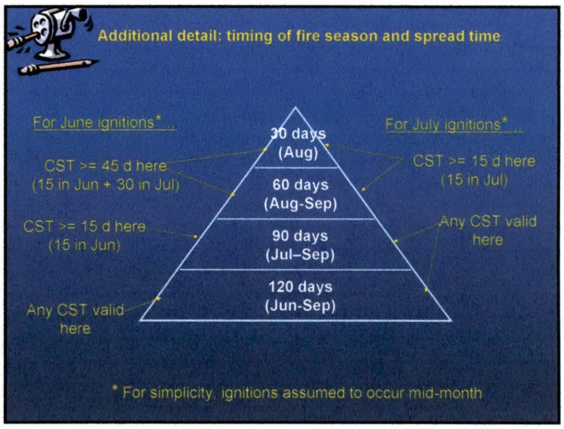
CST to compute *PEnd* and *PNoRain*

Length of Fire Season
CST (640 Grids)
Rain Frequency
=
X
PBurn
PEnd
PNoRain

640 Probability Grids

$$PEnd = \exp\left[-\left(\frac{CST}{\text{season length}}\right)^{\eta}\right]$$

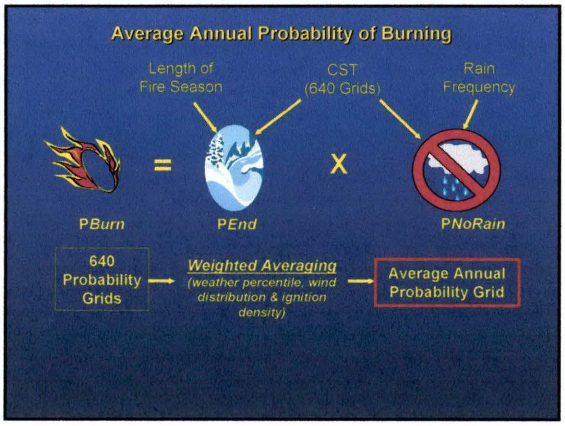
$$PNoRain = 1 - PRain$$



Additional detail: timing of fire season and spread time

For June ignitions*...
CST >= 45 d here (15 in Jun + 30 in Jul)
CST >= 15 d here (15 in Jun)
Any CST valid here
30 days (Aug)
60 days (Aug-Sep)
90 days (Jul–Sep)
120 days (Jun-Sep)
For July ignitions*...
CST >= 15 d here (15 in Jul)
Any CST valid here

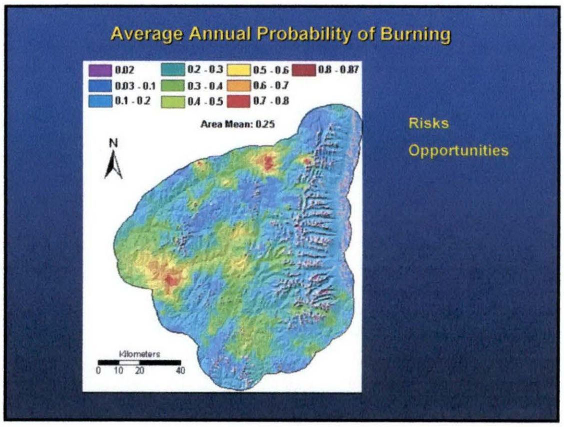
* For simplicity, ignitions assumed to occur mid-month



Average Annual Probability of Burning

Length of Fire Season
CST (640 Grids)
Rain Frequency
=
X
PBurn
PEnd
PNoRain

640 Probability Grids → *Weighted Averaging* *(weather percentile, wind distribution & ignition density)* → Average Annual Probability Grid

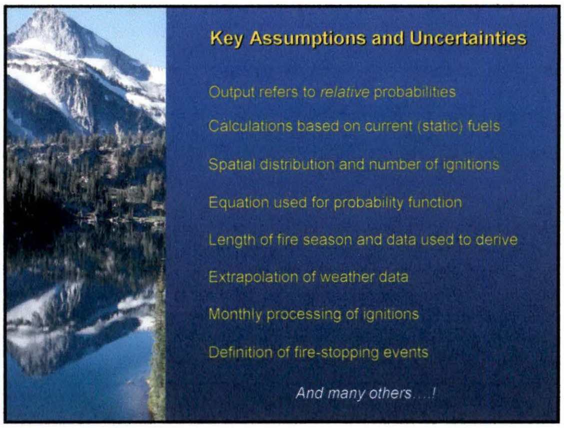


Average Annual Probability of Burning

0.02
0.03 - 0.1
0.1 - 0.2
0.2 - 0.3
0.3 - 0.4
0.4 - 0.5
0.5 - 0.6
0.6 - 0.7
0.7 - 0.8
0.8 - 0.87
Area Mean: 0.25
N
Kilometers
0
10
20
40

Risks

Opportunities



Key Assumptions and Uncertainties

Output refers to *relative* probabilities

Calculations based on current (static) fuels

Spatial distribution and number of ignitions

Equation used for probability function

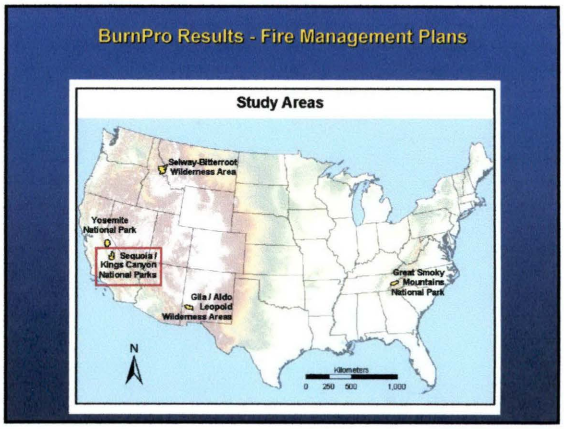
Length of fire season and data used to derive

Extrapolation of weather data

Monthly processing of ignitions

Definition of fire-stopping events

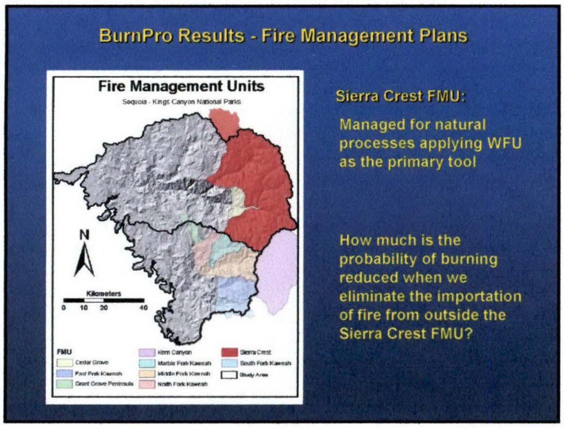
And many others…!



BurnPro Results - Fire Management Plans

Study Areas

Selway-Bitterroot Wilderness Area
Yosemite National Park
Sequoia / Kings Canyon National Parks
Gila / Aldo Leopold Wilderness Areas
Great Smoky Mountains National Park
N
Kilometers
0 250 500 1,000



BurnPro Results - Fire Management Plans

Fire Management Units

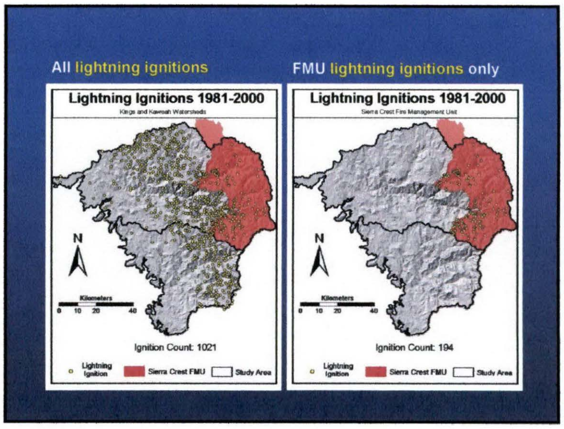
Sequoia - Kings Canyon National Parks

N
Kilometers
0 10 20 40
FMU
Cedar Grove
East Fork Kaweah
Grant Grove Peninsula
Kern Canyon
Marble Fork Kaweah
Middle Fork Kaweah
North Fork Kaweah
Sierra Crest
South Fork Kaweah
Study Area

Sierra Crest FMU:

Managed for natural processes applying WFU as the primary tool

How much is the probability of burning reduced when we eliminate the importation of fire from outside the Sierra Crest FMU?



All lightning ignitions

Lightning Ignitions 1981-2000

Kings and Kaweah Watersheds

Ignition Count: 1021

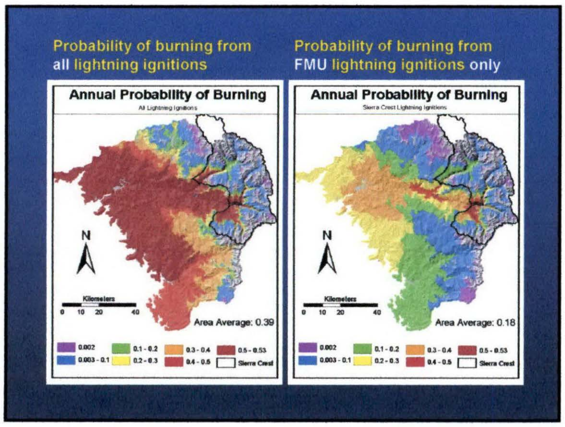
FMU lightning ignitions only

Lightning Ignitions 1981-2000

Sierra Crest Fire Management Unit

Ignition Count: 194

N
Kilometers
0 10 20 40
Lightning Ignition
Sierra Crest FMU
Study Area



Probability of burning from all lightning ignitions

Annual Probability of Burning

All Lightning Ignitions

Area Average: 0.39

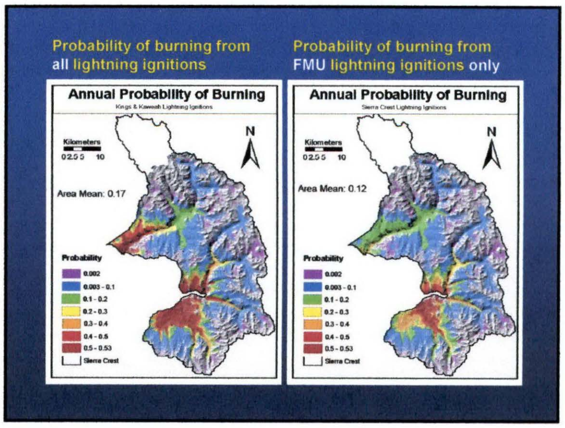
Probability of burning from FMU lightning ignitions only

Annual Probability of Burning

Sierra Crest Lightning Ignitions

Area Average: 0.18

N
Kilometers
0 10 20 40
0.002
0.003 - 0.1
0.1 - 0.2
0.2 - 0.3
0.3 - 0.4
0.4 - 0.5
0.5 - 0.53
Sierra Crest



Probability of burning from all lightning ignitions

Annual Probability of Burning

Kings & Kaweah Lightning Ignitions

Area Mean: 0.17

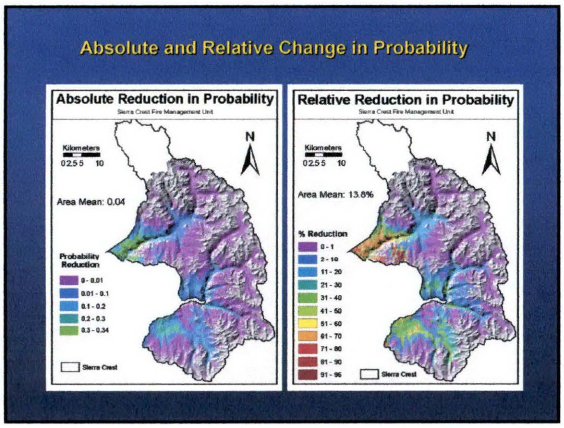
Probability of burning from FMU lightning ignitions only

Annual Probability of Burning

Sierra Crest Lightning Ignitions

Area Mean: 0.12

N
Kilometers
0 2.5 5 10
Probability
0.002
0.003 - 0.1
0.1 - 0.2
0.2 - 0.3
0.3 - 0.4
0.4 - 0.5
0.5 - 0.53
Sierra Crest



Absolute and Relative Change in Probability

Absolute Reduction in Probability

Sierra Crest Fire Management Unit

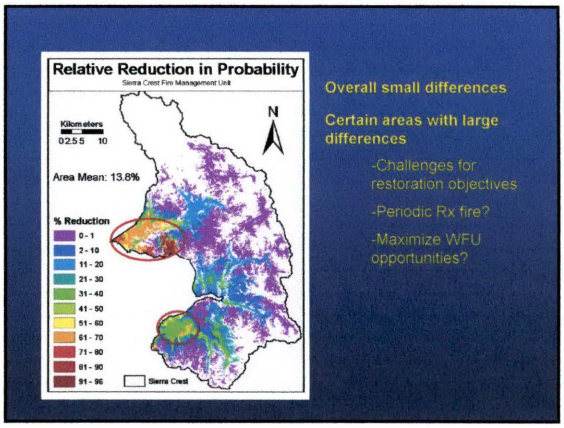
Area Mean: 0.04

Relative Reduction in Probability

Sierra Crest Fire Management Unit

Area Mean: 13.8%

Kilometers
0 2.5 5 10
N
Probability Reduction
0 - 0.01
0.01 - 0.1
0.1 - 0.2
0.2 - 0.3
0.3 - 0.34
Sierra Crest
% Reduction
0 - 1
2 - 10
11 - 20
21 - 30
31 - 40
41 - 50
51 - 60
61 - 70
71 - 80
81 - 90
91 - 96



Relative Reduction in Probability

Sierra Crest Fire Management Unit

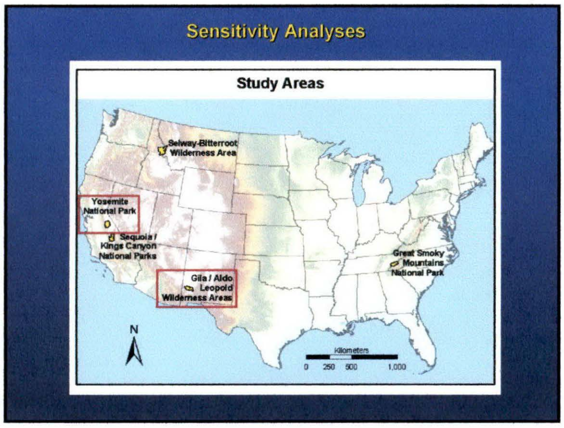
Area Mean: 13.8%

Kilometers
0 2.5 5 10
N
% Reduction
0 - 1
2 - 10
11 - 20
21 - 30
31 - 40
41 - 50
51 - 60
61 - 70
71 - 80
81 - 90
91 - 96
Sierra Crest

Overall small differences

Certain areas with large differences

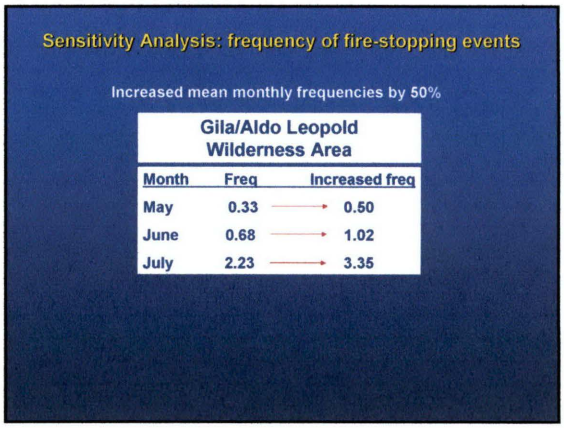
- -Challenges for restoration objectives
- -Periodic Rx fire?
- -Maximize WFU opportunities?



Sensitivity Analyses

Study Areas

Selway-Bitterroot Wilderness Area
Yosemite National Park
Sequoia / Kings Canyon National Parks
Gila / Aldo Leopold Wilderness Areas
Great Smoky Mountains National Park
N
Kilometers
0 250 500 1,000

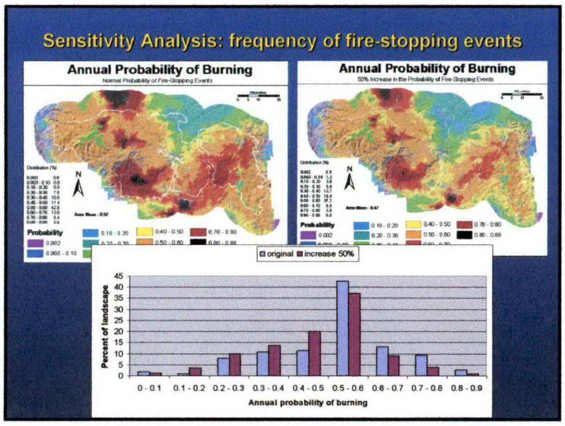


Sensitivity Analysis: frequency of fire-stopping events

Increased mean monthly frequencies by 50%

Gila/Aldo Leopold Wilderness Area

Month	Freq		Increased freq
May	0.33	→	0.50
June	0.68	→	1.02
July	2.23	→	3.35



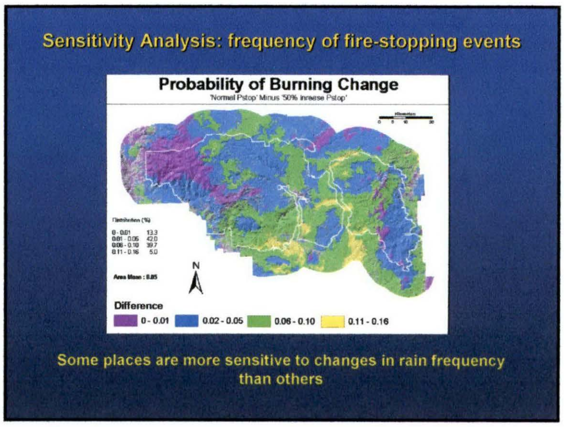
Sensitivity Analysis: frequency of fire-stopping events

Annual Probability of Burning

Normal Probability of Fire-Stopping Events

Annual Probability of Burning

50% Increase in the Probability of Fire-Stopping Events



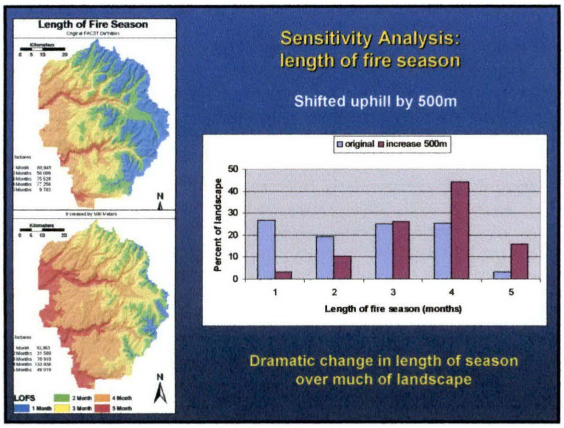
Sensitivity Analysis: frequency of fire-stopping events

Probability of Burning Change

'Normal Pstop' Minus '50% inrease Pstop'

Distribution (%)
0 - 0.01 13.3
0.01 - 0.05 42.0
0.06 - 0.10 39.7
0.11 - 0.16 5.0
Area Mean : 0.05
N
Difference
0 - 0.01
0.02 - 0.05
0.06 - 0.10
0.11 - 0.16

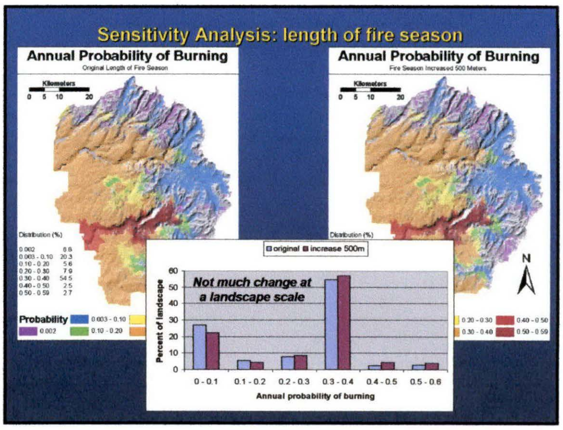
Some places are more sensitive to changes in rain frequency than others



Sensitivity Analysis: length of fire season

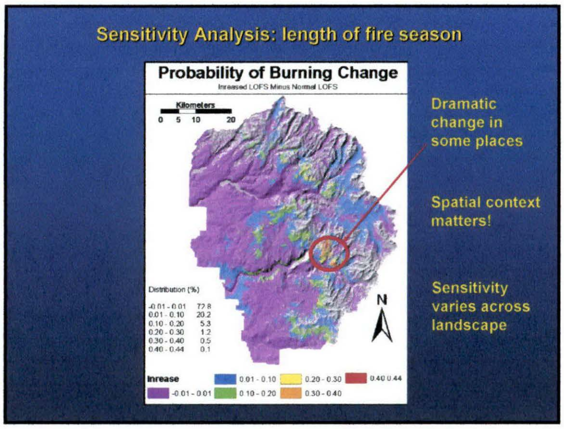
Shifted uphill by 500m

Dramatic change in length of season over much of landscape



Sensitivity Analysis: length of fire season

Not much change at a landscape scale



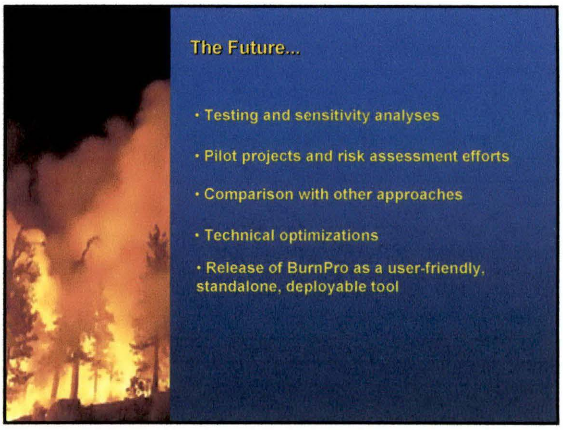
Sensitivity Analysis: length of fire season

Dramatic change in some places

Spatial context matters!

Sensitivity varies across landscape

Probability of Burning Change
Inreased LOFS Minus Normal LOFS
Kilometers
0 5 10 20
Distribution (%)
-0.01 - 0.01 72.8
0.01 - 0.10 20.2
0.10 - 0.20 5.3
0.20 - 0.30 1.2
0.30 - 0.40 0.5
0.40 - 0.44 0.1
N
Inrease
-0.01 - 0.01
0.01 - 0.10
0.10 - 0.20
0.20 - 0.30
0.30 - 0.40
0.40 0.44



The Future…

- Testing and sensitivity analyses
- Pilot projects and risk assessment efforts
- Comparison with other approaches
- Technical optimizations
- Release of BurnPro as a user-friendly, standalone, deployable tool